AUTOMATIC VOLTAGE REGULATOR FOR AN INDUCTION GENERATOR

Malcolm Emery Clark
Donald Earl Craig
and
Robert William Slater

Letter on front cover:

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by

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ABSTRACT

Title of thesis: Automatic Voltage Regulator for an Induction Generator

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Submitted for the degree of Naval Engineer in the Department of Naval Architecture and Marine Engineering on May 24, 1954.

In previous investigations of the operation of capacitor-excited induction generators, the size of capacitors in the network coupling the load to the generator have been selected by trial and error, and a satisfactory coupling network has never been developed. It was attempted herein to develop a satisfactory coupling network by choosing the capacitors in the sizes required to accomplish definite results.

There were three preliminary steps:
(1) The induction generator terminal characteristic was determined experimentally and verified.
(2) A method of analyzing and predicting the effects of various coupling networks was conceived, used, and verified.
(3) It was proved that series-capacitor-coupled induction generators will produce sustained fault currents.

A network for coupling unity power factor loads to an induction generator in such a manner as to maintain constant load voltage was developed, analyzed, and tested, but the test results do not permit conclusive evaluation.

An attempt was made to develop a coupling network for variable inductive loads to produce coarse voltage regulation so that fine control could be achieved with a smaller D-C controlled saturable reactor than would be needed otherwise. Such a network was devised, and the optimum parameter adjustment was determined by analysis. The network was tested and found to produce coarse voltage regulation; however, it was found that the use of this network does not appreciably reduce the size of the reactor needed for fine control of voltage. This network does have value in protecting the load and generator from harmonic currents arising from the use of the reactor, and it is recommended as the basis for the design of an automatic voltage regulator with a slightly different adjustment of parameters.

Cambridge, Massachusetts,
May 24, 1954.

Professor Leicester F. Hamilton,
Secretary of the Faculty,
Massachusetts Institute of Technology,
Cambridge, Massachusetts.

Dear Professor Hamilton;

In accordance with the requirements of the degree of Naval Engineer, we herewith submit a thesis entitled "Automatic Voltage Regulator for an Induction Generator".

Very respectfully,

ACKNOWLEDGEMENT

The authors desire to express their appreciation to Professor Kusko for his advice and guidance, to Dr. J. B. Friauf of the Bureau of Ships for his advice, and to Harvey Solomon, John Rafferty, and Don Buerschinger of the U. S. Naval Boiler and Turbine Laboratory for their fine cooperation.

Automatic Voltage Regulator

for an Induction Generator

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Chapter I

INTRODUCTION

The demand for lighter electrical equipment for ships, aircraft, and missles has created a need for high-speed electrical rotating machines, including polyphase a-c generators; however, the stresses in the windings and insulation on the rotor and in the rotor steel itself, produced by centrifugal force, must not exceed certain magnitudes. This circumstance limits the allowable rotational speed of synchronous generators and motors. The limitation imposed by centrifugal stresses can be avoided by using squirrel-cage or solid-rotor induction machines, which have, respectively, neither insulation nor winding on the rotor. Because of the simple rotor construction, induction machines, excepting the wound-rotor types, are much cheaper, smaller, and lighter than their synchronous counterparts. These advantages become even more marked when full advantage is taken of the higher permissible rotational speeds.

Induction machine theory has been thoroughly developed because of the great number of induction motors in use, but this theory has not been extended to a method of controlling the voltage of an induction generator being operated as the sole source of electrical power in an isolated system and supplying power to a wide range of inductive loads such as are found aboard a ship. Connected in proper phase sequence to a large system containing a number of synchronous

generators in central stations, an induction generator will draw enough reactive excitation power from the system to operate at the system voltage and frequency, while converting into electrical power whatever mechanical power is supplied to it by its prime mover. In this case, there is no need for special devices to control the frequency and voltage of the induction generator. However, an induction generator is an inductive circuit element, and it can not supply reactive power to inductive loads in an isolated system. In fact, an induction generator must itself be excited by capacitive elements in the connected circuit, and these capacitive elements must also provide excitation currents to any inductive loads. An induction generator is not entirely equivalent to a synchronous generator in this respect, but the induction generator plus its excitation equipment is generally smaller, lighter, and cheaper than an equivalent synchronous generator.

In an isolated electrical system where an induction generator is to be used to supply inductive loads, there must be a coupling network between the generator and the load to serve the following purposes:

(1) accomodate the exchange of reactive energy with both the generator and the load in the amounts necessary to maintain the load voltage nearly constant

(2) pass the real power from the generator to the load without dissipating much real power

(3) cause the generator to produce large sustained currents under short-circuit conditons at the load terminals, and pass sufficient current during the short circuit to actuate selective switching by circuit breakers to clear the fault.

No satisfactory coupling network has ever been developed. Networks which will provide voltage regulation are known, but these invariably have poor short-circuit characteristics. Other networks are known shich will produce sustained short-circuit currents, but the voltage regulation is poor. It can be said in general that capacitive coupling produces good regulation, while induction coupling has satisfactory short-circuit characteristics.

In most experimental work with self-excited induction generators, a shunt capacitor in each phase has been used to provide excitation. Unfortunately, a short circuit across this configuration will result in complete loss of excitation, since there is no capacitance, as seen from the generator terminals, to provide excitation. As previously mentioned, one of the requirements of a successful regulator is that a consequence of a short circuit is a sustained current. A shunt capacitor, however, will be used as a basic starting point for the design of a successful voltage regulating network.

There are a number of possible configurations which immediately present themselves for consideration. Certainly the two most obvious are series inductor coupling and series

capacitor coupling. These have the drawbacks previously mentioned, however.

A number of writers have recognized that by making the shunt capacitance continously adjustable, constant voltage can be maintained. One method of achieving the effect of variable capacitance is to place a variable inductance, such as a direct-current controlled saturable reactor, in parallel with the shunt capacitance. This presents a problem in feedback control, if automatic control is desired, but it should not be a difficult problem. Unless coarse voltage regulation is provided by a network, and the saturable reactor used only for fine control, the feedback components may become unduly large, however. Such a combination of saturable reactor and shunt capacitance, if used alone, would unfortunately again result in voltage collapse as an inevitable consequence of a short circuit at the load terminals, and it becomes evident that some additional elements are required between the 'variable capacitance' and the load.

A number of attempts have been made to determine the makeup of these additional elements. Most investigators have used inductive coupling, evidently in the belief that inductive coupling is necessary for suitable short-circiut performance. The use of inductive elements has the disadvantages of relatively large voltage drop between the generator and the load, the large physical size, and the small short circuit currents obtained. Harmonic distortion is always a

problem when a non-linear device such as a saturable reactor is used, but this problem is present whether or not inductive coupling is used, and can be minimized by connecting the a-c windings of the saturable reactor in series and by connecting the three phase output in delta. These two steps will result in the complete elimination of second and third harmonics, and any integral multiples thereof.

The various investigators in this field have generally found a certain range of loads that result in nearly constant load voltage, but the ranges have not been large enough to be useful. Thses earlier attempts have all been trial and error experimental work so that the conditions of constant load voltage have generally been achieved accidentally. Certainly there are configurations that tend to produce constant load voltage, and thereby reduce the range of control required of a saturable reactor. This thesis is a study of more complicated coupling circuits, and the authors will attempt to develop a broader view of the effects of various loads upon load voltage, and also develop a method of mapping load voltage as a function of load admittance or impedance.

Chapter II

PROCEDURE

2.1 Induction Generator Terminal Characteristics

The first step in the laboratory was to determine the terminal characteristic of the induction generator being tested. The steady-state terminal characteristic was to be represented as lines of constant terminal voltage plotted on coordinates of conductance and capacitive susceptance of the load.

Test Circuit No. 1, Figure I, was used for this test. This circuit shows an induction generator being driven by a D-C shunt motor. The generator load consisted of a stove of calibrated resistors paralleled with fixed load capacitors connected through a variac in each phase, with the three phases delta-connected. The conductance was held constant during a set of runs and could be varied among four values and open-circuit by switching. The capacitive susceptance of the load was varied by means of the three-phase variac and was changed before each run.

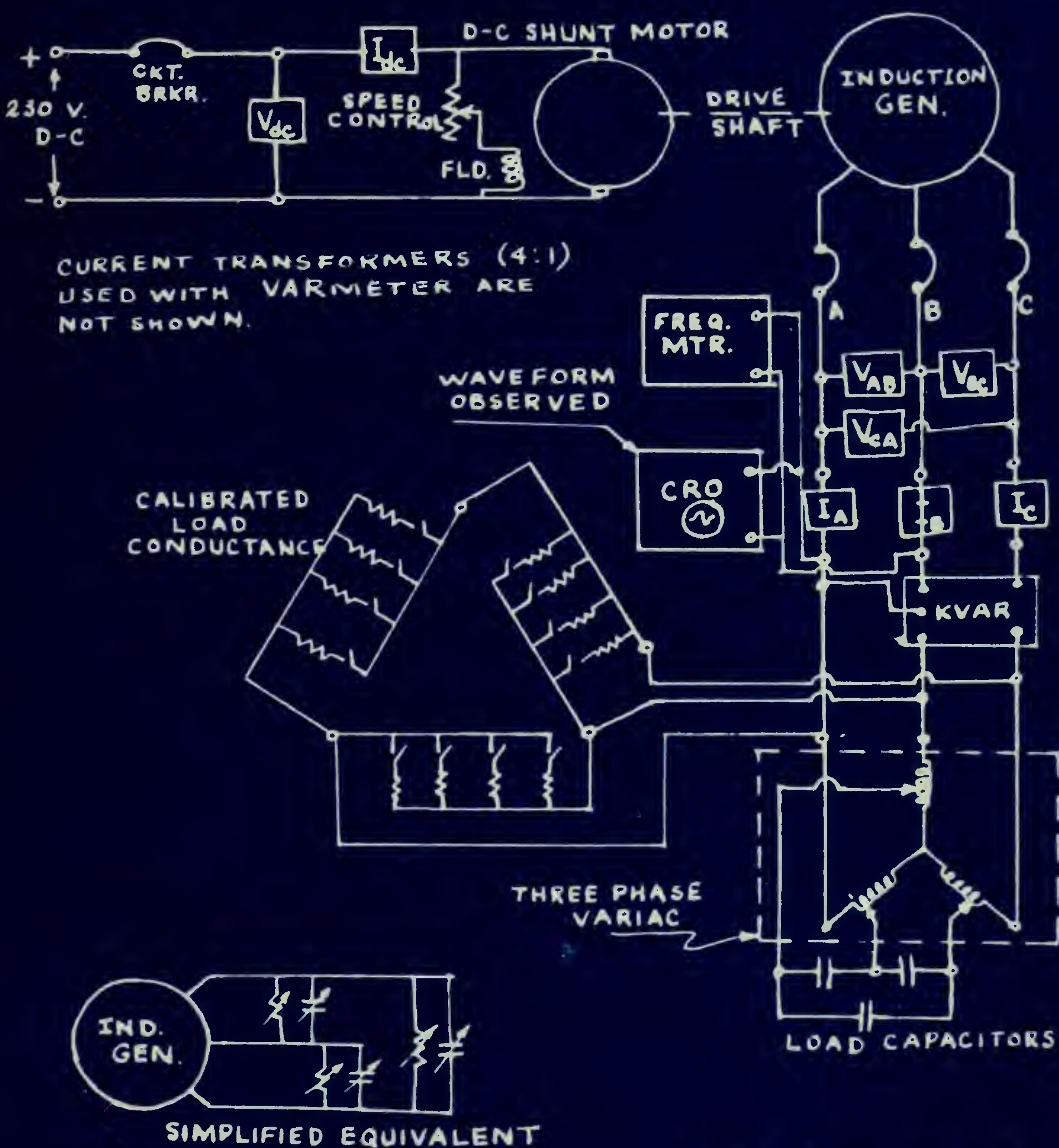
The frequency meter was checked against the Boston Edison System and found to have no error at 60 cps. The frequency was adjusted by means of a rheostat in the D-C motor field circuit to within 0.10 cps of 60 cps before each run, and recorded for each run. Voltages and currents at the terminals of both the motor and generator were measured with laboratory meters accurate to within 1% of full scale. An oscilloscope was used to observe the generator voltage waveform. A

FIGURE I

TEST CIRCUIT NO. 1

USED TO OBTAIN

INDUCTION GENERATOR CHARACTERISTIC



TEST RUNS 1 TO 7

PLATE 2-I

varmeter was used with 4:1 current transformers not shown on the diagram to measure reactive power at the generator terminals. A wattmeter could not be used because the generator operated at power factors less than 0.5 most of the time, and the wattmeters available were not accurate at such low power factors.

The data required to plot the generator terminal voltage map was the generator voltage, the terminal conductance of the load, and the capacitive susceptance of the load. The voltage was obtained by averaging the three observed values of generator terminal voltage. The susceptance was determined by dividing the total reactive power by the square of the average terminal voltage. For balanced operation, the number so obtained is equal to the sum of the susceptances of all three phases of a delta-connected load or the susceptance of a single phase of an equivalent wye-connected load. An estimate of real power was obtained by calculating the vector difference of the volt-ampere product and the reactive power. This value of real power was divided by the square of the average voltage to obtain an estimate of load conductance. This estimate was compared to the recorded values of calibrated conductance. The estimate was in every case larger than the calibrated value, but the differences for various conditions compared well. The comparison was made to obtain a value of conductance of meters, leads, and variac windings, this value being the mean excess of conductance of the estimate compared to the calibrated value. The conductance of the resistors was

[illegible]

obtained by the voltmeter-ammeter method. Great accuracy was not required for this work because any voltage regulator system would have to be adjusted after installation anyway. The purpose was to obtain data sufficiently accurate to design components of a voltage regulator.

2.2 Series Capacitor Coupling

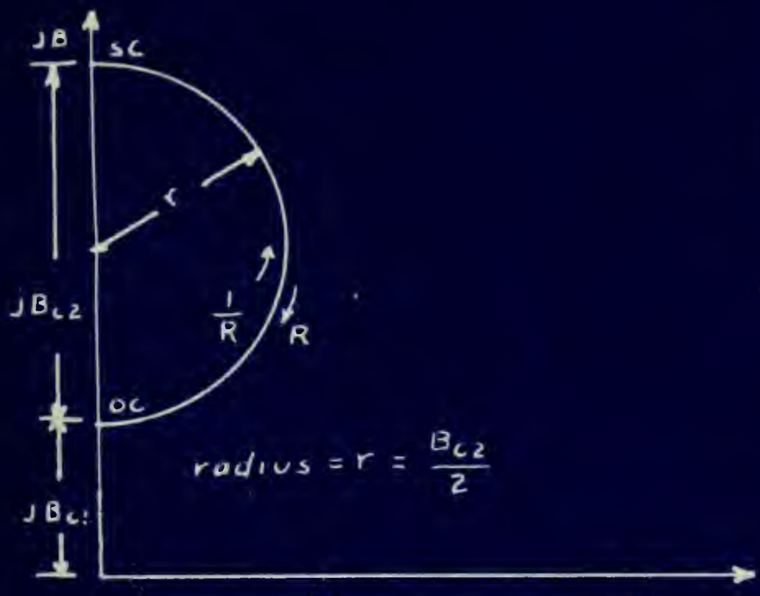
This test was intended to serve two purposes:

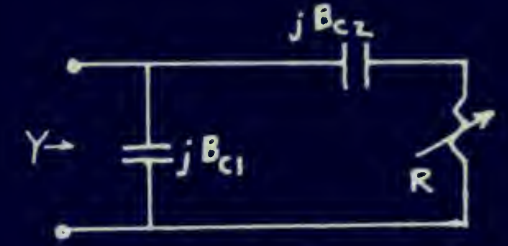
(1) To demonstrate that a simple, small, lightweight, capacitive coupling network could be used to regulate the voltage of an induction generator electrical power supply to a unity-power factor load, such as electronic load or compensated load in some missile and aircraft applications where the light weight and compactness of the induction generator would be particularly advantageous

(2) To prove that short-circuit currents large enough to actuate selective switching on shipboard or to burn off faults in aircraft systems can be sustained by capacitively coupled induction generators. Previous trial work by Swift (21) had shown that capacitive coupling with shunt and series capacitors tended to produce nearly constant voltage at the generator terminals for certain conditons, but it was generally accepted that such a configuration would not cause the generator to produce sustained short circuit currents.

2.2.1 Theoretical Consideration of Series Capacitor Coupling

Figure II is a circuit diagram of a single phase of a unity power factor load and a capacitive coupling network, which is called a gamma network by the authors because the





Y = G + jB

FIGURE II.
GAMMA NETWORK.

FIGURE III

Locus of admittance of capacitor-coupled unity power factor load

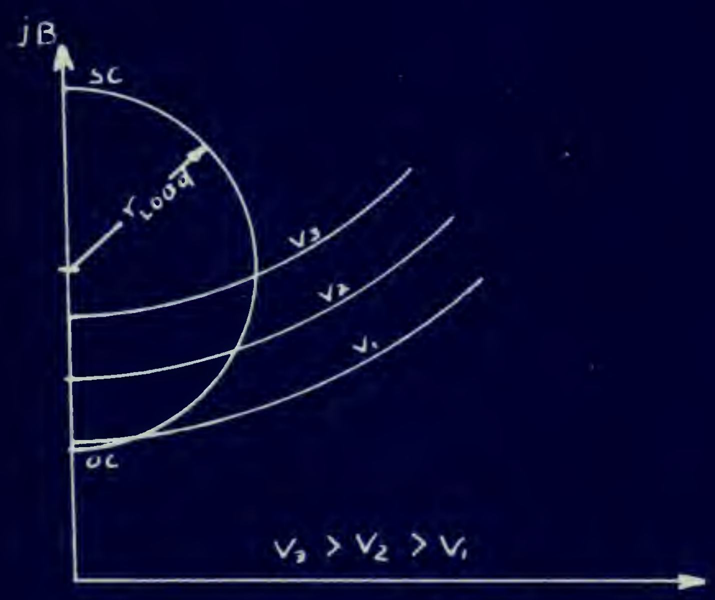


FIGURE IV

Admittance locus superposed on generator characteristic

capital letter gamma suggests the configuration of the capacitors. The admittance of the coupling network and the load as viewed from the generator terminals is:

$$Y_{gen} = jB_{c1} + \frac{1}{R + 1/jB_{c2}} \qquad (1)$$

where R is a variable quantity. Figure III shows the locus of this admittance as R varies. The position of the center of the semicircular locus can be controlled by varying the value of shunt capacitance B_{c1}, and the radius of the semicircle is determined by the value of the series capacitive susceptance B_{c2}. It is apparent that if the capacitances were adjusted so that this locus were superposed on an arc of constant generator voltage on the admittance diagram voltage map of the generator characteristic, the generator voltage would remain nearly constant as the value of the load resistor R was varied. This adjustment would produce constant generator voltage, but constant voltage at the load is the desired result. If the value of the series capacitance were reduced a little from the value to maintain constant generator voltage, the generator voltage would tend to increase as the value of R decreased as shown in Figure IV. With some adjustment of the series capacitance, it is possible that the rate of increase in generator voltage as R decreased would be equal to the increase in voltage drop across the series capacitor. An exact solution is not possible with this coupling network because the center of the locus semicircle lies on the vertical axis while the centers of the voltage arcs lies to the left of the vertical axis due to the effect of the generator

stator leakage inductance. The slope of the locus is zero at the open-circuit point, but the arc of constant generator voltage passing through this point must have a positive slope at this point; therefore, the generator voltage and load voltage must decrease slightly as R is reduced from open-circuit to some large finite value. This effect could be largely overcome by using another capacitor in the coupling network to cancel out the effect of the stator leakage inductive reactance. The capacitors would then form a tee network instead of a gamma network, but this refinement is probably unnecessary.

To determine whether or not an additional capacitor would be desirable, an analytical solution was carried out to determine what results could be obtained with the optimum value of capacitor in the gamma network. The experimentally determined voltage map of generator characteristics was used in this analysis and the calculations are presented in Appendix D. This calculation indicated that the load voltage could be maintained within 2 volts of 150 volts for B_{c1} equal to 0.033 mho and B_{c2} equal to 0.116 mho with the three phases delta-connected. This result was considered to indicate that the additional capacitor was unnecessary.

The short-circuit point on the locus of the admittance viewed from the generator terminals is marked SC on Figure III, and it can be seen that this point corresponds to a large generator voltage. Since this voltage would be imposed across

the series capacitor when the resistor R was shorted, a large current could be expected to flow through the short circuit. The actual transient path can not be drawn on the voltage map for 60 cps operation because the frequency changes during the transient phenomenon. Notice that there is very little resistance in the circuit after the short occurs and that the current through this small resistance is limited by a capacitor in each branch; therefore the load can absorb very little real power. Before the short circuit, the generator may have been operating well above synchronous speed with a large magnitude of slip required to deliver the real power, and the rotor can not decelerate suddenly because of mechanical inertia. After the short occurs, the real power and slip decrease suddenly; therefore, the frequency and the synchronous speed must increase. The increase in frequency results in a greater rise in generator voltage than is indicated by the steady state locus on the voltage map for 60 cps. An approximate analysis of the short-circuit transient can be made either by assuming an analogous synchronous generator (23) or by linear circuit analysis of an equivalent circuit with time-varying circuit parameters. The authors do not believe that this will be necessary in the design of any practical voltage regulator because the reactance of the series capacitor will always be limited by the allowable voltage drop across the capacitor when full-load current flows through it. Corresponding to this small allowed value of reactance, the susceptance of the series capacitor will always be large enough to produce a

suffiencently large short-circuit current. Notice that the line drawn from any operating condition to the short-circuit point, which is assumed to indicate roughly the transient path, will never cross the arc representing the minimum steady state voltage.

The remarks above apply to a three-phase short circuit. It was assumed that roughly the same phenomenon would occur in the shorted phase with a single-phase short, and that the voltage in the other two phases would rise temporarily until the fault was cleared. It is believed that the excess of susceptance will always be sufficient to clear single-phase faults.

2.2.2 Laboratory Procedure

Test circuit No. 2, Figure V, was used for runs 6 through 14, and test circuit No. 3, Figure VI, was used for runs 15 through 22. In the former circuit the series capacitors were coupled into the circuit by 4:1 stepdown transformers, and in the latter circuit the series capacitors were connected directly into the circuit. In both circuits the load consisted of a bank of resistors coupled to the generator by a gamma network with the three phases connected in delta. The resistors were calibrated in mhos and arranged to permit switching in increments of 0.0111 mho, from zero to 0.0444 mho per phase. In most cases, the conductance of 0.0333 mho per phase fully loaded the D-C shunt motor driving the generator. As indicated by the labels on the diagrams of meters in the circuit diagrams, the current, voltage across the resistor, and the voltage across the series capacitor were measured in each

FIGURE V

TEST CIRCUIT NO. 2

USED TO TEST GAMMA NETWORK WITH TRANSFORMERS

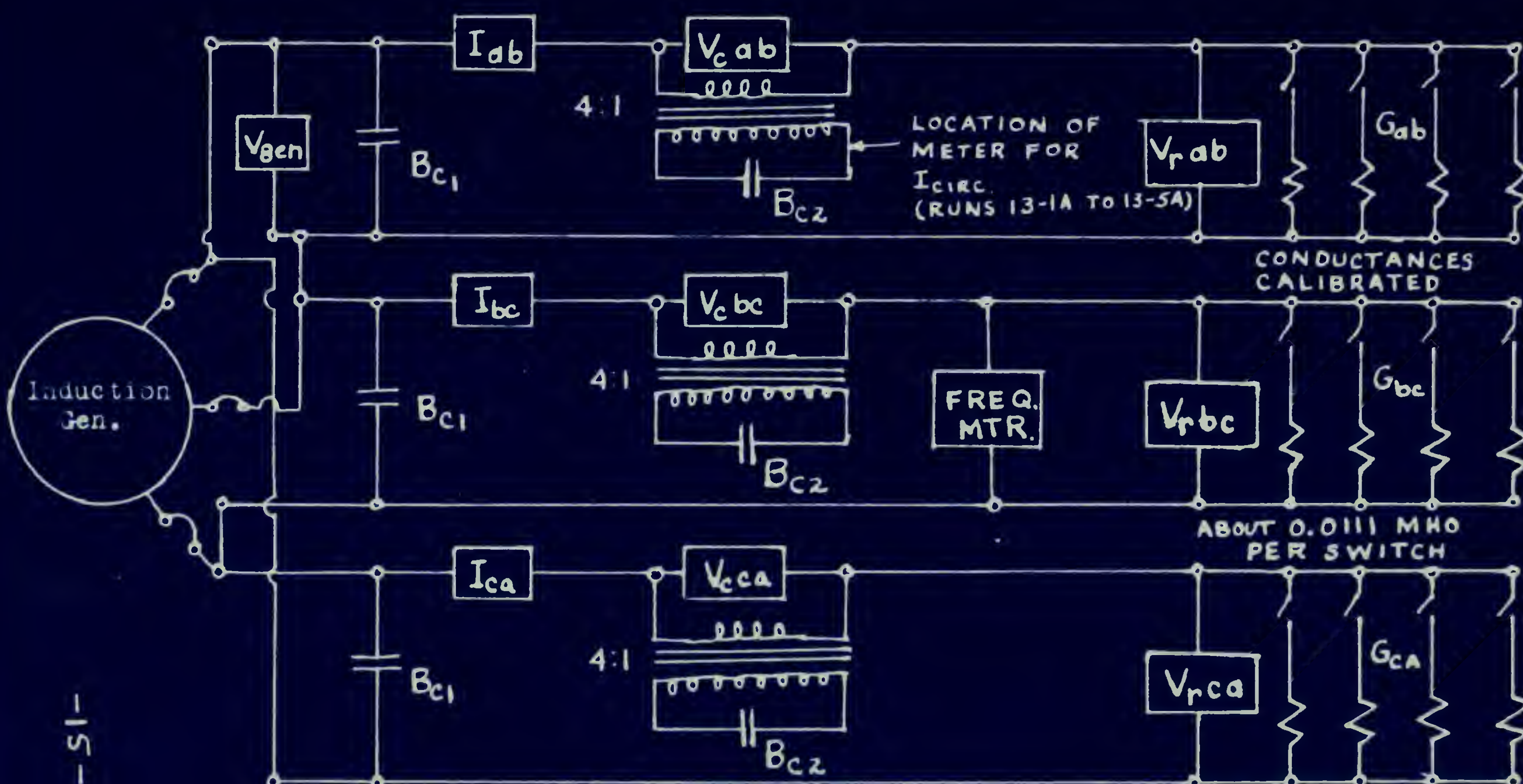
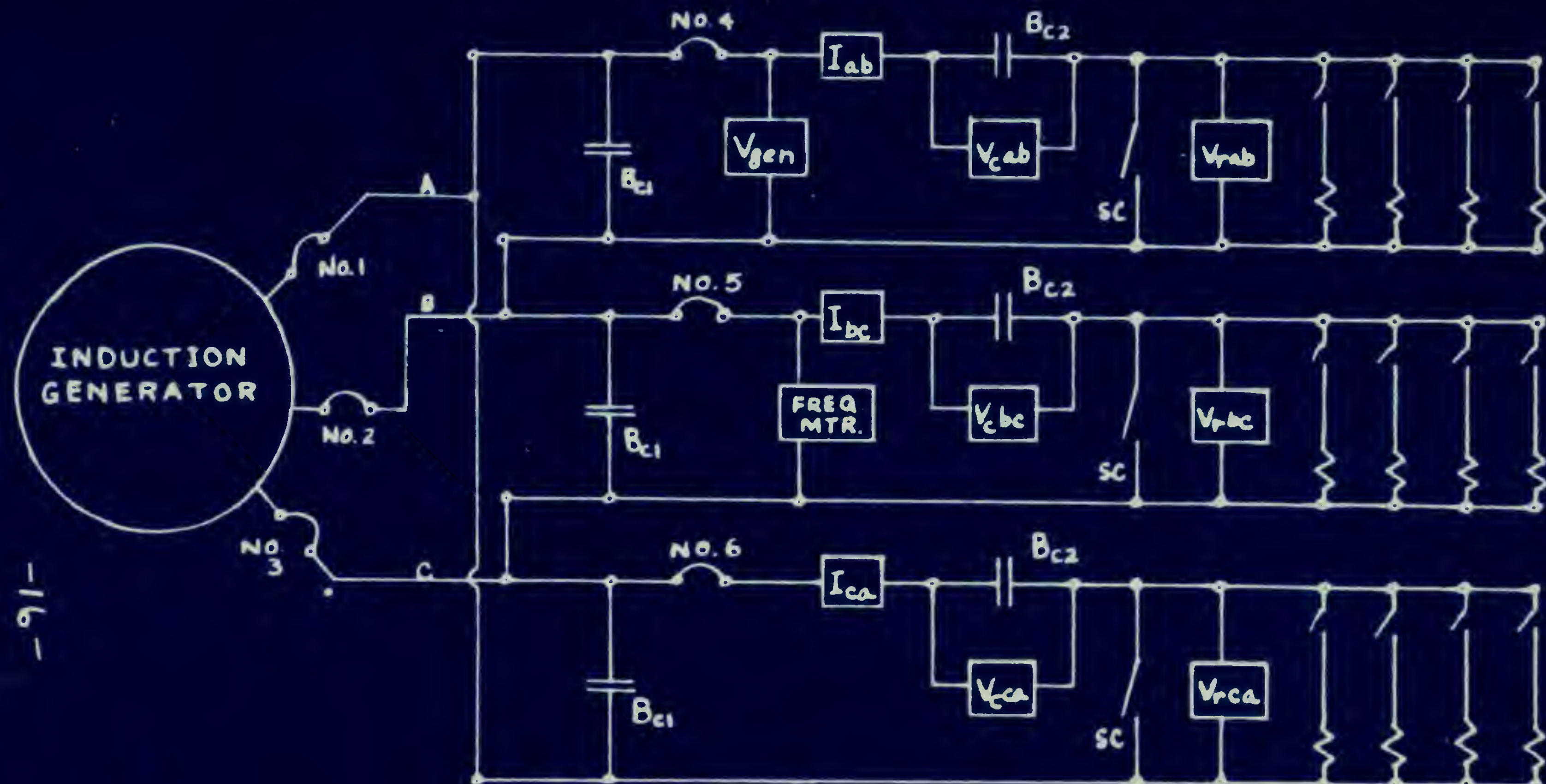


FIGURE VI
TEST CIRCUIT NO. 3
GAMMA NETWORK WITHOUT TRANSFORMERS



phase, and the generator voltage and frequency were measured in one phase. In runs 13-1A to 13-5A, an additional ammeter was inserted between the transformer secondary winding and the series capacitor, in order to verify the theory that local resonance was occurring and producing the unusual phenomenon encountered in this set of runs. The notation on the meters corresponds exactly to the notation in the tables of data in Appendices C and F.

Runs 6 through 18 were all of one type. In these runs, the loads in all three phases were kept balanced and the frequency was always adjusted to 60 cps. The values of the capacitors were kept fixed during the run, and the meters were read after each change in conductance. After each run, the series capacitance was readjusted to a value closer to the optimum value, i.e., the value that tended to produce the least change in load voltage with a change of load. The open-circuit voltage was about 150 volts for runs 6 through 10, 180 volts for runs 11 through 13 and 15 through 18, and 205 volts for run 14.

Run 19 was observed in order to obtain preliminary information for the unbalanced load test. In run 20 the capacitors were adjusted to the optimum value for 180 volts, and the load was added in increments of 0.0111 mho per phase, with the three phases always balanced. Then the load was removed in increments of 0.0111 mho per phase, one phase at a time. In the extreme conditons, one phase was open-circuited with two phases fully loaded, and two phases were

completely open-circuited while one phase was fully loaded. The purpose of this test was to observe the effect of phase unbalance upon the load voltage. The frequency was maintained throughout this test at 60 cps.

Using the same values of capacitance in run 21, the load was added with all three phases balanced with the frequency very carefully adjusted to 60.00 cps. before each reading. In run 22 the same procedure was followed except that the frequency was never readjusted after having been set at 60 cps for the no load condition. The frequency was allowed to decrease as the D-C motor speed decreased, and the generator slip increased as the load increased. The purpose of this test was to observe the behavior of a gamma-coupled generator without frequency regulation.

After the above tests were completed, all the meters were removed from test circuit No. 3, and a three-phase guillotine switch was connected across the resistors as indicated by the switches marked SC on the circuit diagram. This switch was used to represent a low impedance fault. Circuit breakers Nos. 4, 5, and 6 were set at about 18 amperes, and circuit breakers Nos. 1, 2, and 3 were set at about 60 amperes. Various balanced and unbalanced load conditions were obtained at 60 cps, then the frequency meter was disconnected, and the guillotine switch was closed. This operation was repeated several times each for several conditions including open-circuit and full load on one, two and three phases, and several intermediate conditons. Then the guillotine switch was dis-

connected from two phases and the procedure was repeated for a single-phase short circuit. The purpose of this test was to determine whether or not the generator with this circuit would produce large enough short-circuit currents to allow selective switching.

2.3 Fixed-Element Voltage Regulation

Control of effective capacitance throughout the range required for voltage control of an induction generator by a saturable reactor requires a large and heavy reactor. The purpose of this section of the thesis was to develop a network for coupling the load to the generator in with fixed elements in such a manner that the range of variable capacitance required to maintain a constant load voltage could be considerably reduced. The fixed elements should produce rough voltage regulation, so that fine control of the voltage could be achieved with relatively small saturable reactors. Essentially the same basic idea was used to develop the gamma network, in which the reactive power developed in the series capacitor varies with the square of the load current so that the generator excitation increases as the load increases.

The load range for this test was assumed arbitrarily to be bounded by the unity power factor line to a conductance of 0.125 mho total for three delta-connected phases or 0.125 mho per phase for a wye-connected load, the line of 0.125 mho conductance, the line of 0.100 mho susceptance, and the 0.6 power factor line, as shown in Figure VII. This accounts for a range of inductive loads from unity to 0.6 power factor. In a

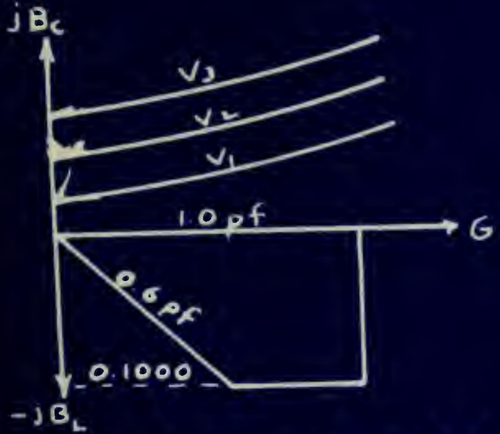


FIGURE VII Assumed Load

FIGURE IX Capacitance required

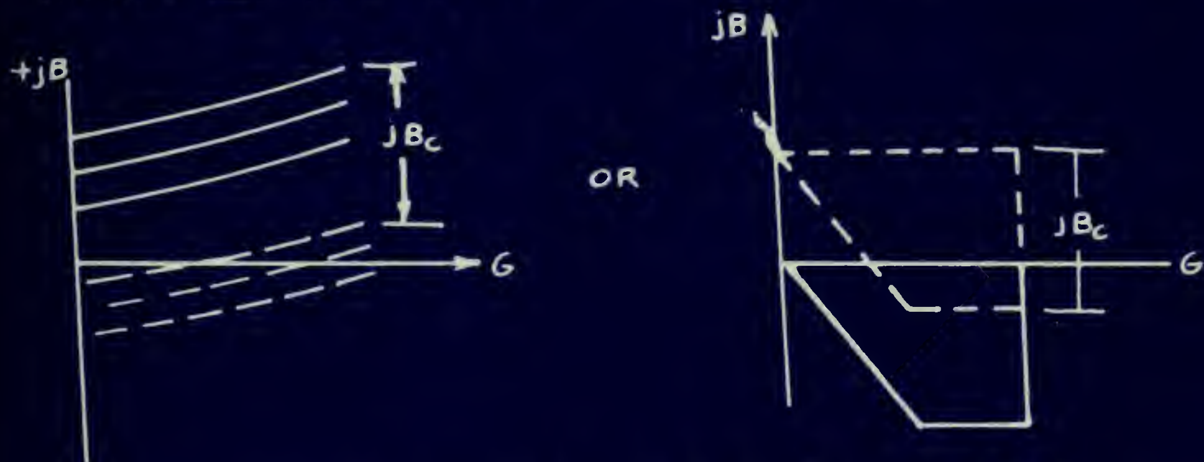


FIGURE VIII Effect of shunt capacitance

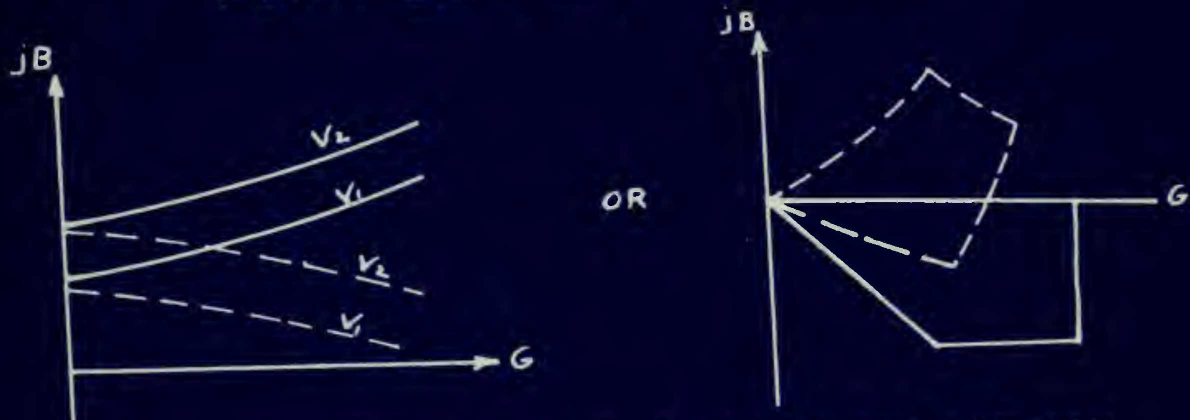


FIGURE X Effect of series capacitance

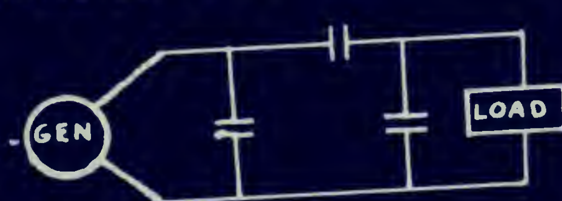


FIGURE XI Pi network

graphical sense, the object of fixed-element regulation is to lower the terminal characteristic of the generator plus the coupling network, and to spread the voltage lines so that this terminal characteristic covers the load range with the voltage arcs spread apart so widely that only the desired load voltage line crosses the load range, i.e., so that the voltage across the whole area representing the load is approximately constant. Conversely, the process may be thought of as inserting a coupling network ahead of the load that will reduce the vertical dimension of the load range area, turn up the right end, and raise the entire area so that the load range appears at the generator terminals as only a thin strip of area centered on the generator characteristic voltage arcs. Figure VIII shows the load range and generator voltage arcs on one diagram. It is apparent that the generator would not be excited if such a load were connected directly to the generator.

2.3.1 Effect of Individual Elements

In order to get some idea of the configuration of fixed elements that should be used to obtain coarse voltage regulation, it is necessary to learn how a particular fixed element changes the characteristic at the terminals preceding the element into a different characteristic at the terminals following the element. Assume that a capacitive susceptance of B_C mho is connected in parallel with any admittance Y; then the admittance of the combination is Y plus jB_C. Now when it is realized that the generator characteristic has been plotted in terms of the load admittance, it is apparent that

the effect of a shunt capacitor connected across the phase leads between the load and the generator is to lower the generator characteristic or to raise the load range by an amount equal to B_c on the admittance diagram, as shown in Figure VIII. Shunt capacitance will accomplish part of the job of a good coupling network. It can be seen that a shunt inductor would have the opposite effect and is, therefore, not desirable. It can also be understood that if only shunt capacitance were used to control the load voltage and to maintain it constant at 200 volts, it would be necessary to control this capacitance over a range of $B_c$max minus B_{c1}, these quantities being indicated on Figure IX.

The effect of series capacitance and series inductance is somewhat more complicated and will not be described in detail at this point. The effect of series capacitance will be revealed by the succeeding paragraphs. Series capacitance tends to spread the voltage arcs of the generator map and to bend down the right end of the characteristic arcs. Conversely, in terms of the load range, series capacitance bends up the right end of the load range and converts the constant voltage area to an area wherein the terminal voltage must increase as the capacitive susceptance increases. Series capacitance also moves the characteristic vertically in the same direction as shunt capacitance, but not in such a simple manner. These effects are illustrated by Figure X, and it can be seen that the effects are desirable. An analysis of series inductance revealed that the effects are just the opposite to

[illegible]

those achieved by series capacitance, as would be expected.

The effects of saturable reactors and resistors were considered in the various configurations studied in developing a fixed element regulator, but no way was found to take advantage of their effects, and the resistors always increase the power loss.

2.3.2 Effect of Several Elements In a Coupling Network

The analysis of the effect of a coupling network composed of several elements can be handled mathematically or graphically if only linear elements are used. If any non-linear elements are used, the graphical technique has a definite advantage. The mathematical expressions involved are lengthy and difficult to understand in terms of physical significance because of their being started from a lengthy linear approximation of the non-linear generator voltage-admittance relation. On the other hand, the graphical technique is quite straightforward, and is easily interpreted into physical significance. This graphical technique takes advantage of the fact that the effect of a shunt reactive element is to cause only a vertical shift of the area being mapped on an admittance diagram, and the effect of a series reactive element is to cause only a vertical shift on an impedance diagram. Resistive elements can be accounted for by horizontal shifts. Lines through the origin on either diagram are lines of constant power factor with the unity power factor line being a horizontal line and with the zero power factor line being a vertical line through the origin. Therefore, angles from the origin are preserved

in converting from one diagram to the other. Finding the optimum values of the various circuit parameters is a laborious process that can be considerably shortened by physical reasoning.

About a dozen likely configurations were analyzed either graphically or mathematically in an attempt to find a coupling network to produce coarse voltage regulation. These possible solutions were conceived by physical reasoning and contained capacitors, inductors, saturable inductors, and resistors. The network producing the best result is described below.

2.3.3 Pi Network

This network consists of a capacitor shunted across the generator, another capacitor shunted across the load, and a third capacitor connected in series between the two as shown by the single-phase diagram of Figure XI. The phases can be connected in either wye or delta, of course, but the delta connection was used in the laboratory since the delta-configuration requires only one-third as much capacitance in series and across the load. The wye connection should be used in larger systems to avoid the necessity of having six wires to supply various loads. The optimum solution was found by plotting the admittance and impedance diagrams for several values of the various capacitors. This process indicated that the optimum is not sharply defined. The analysis that follows involves parameters that are very close to optimum.

Figure XII shows the load range shifted upward 0.075 mho on the admittance diagram. The amount of this shift is deter-

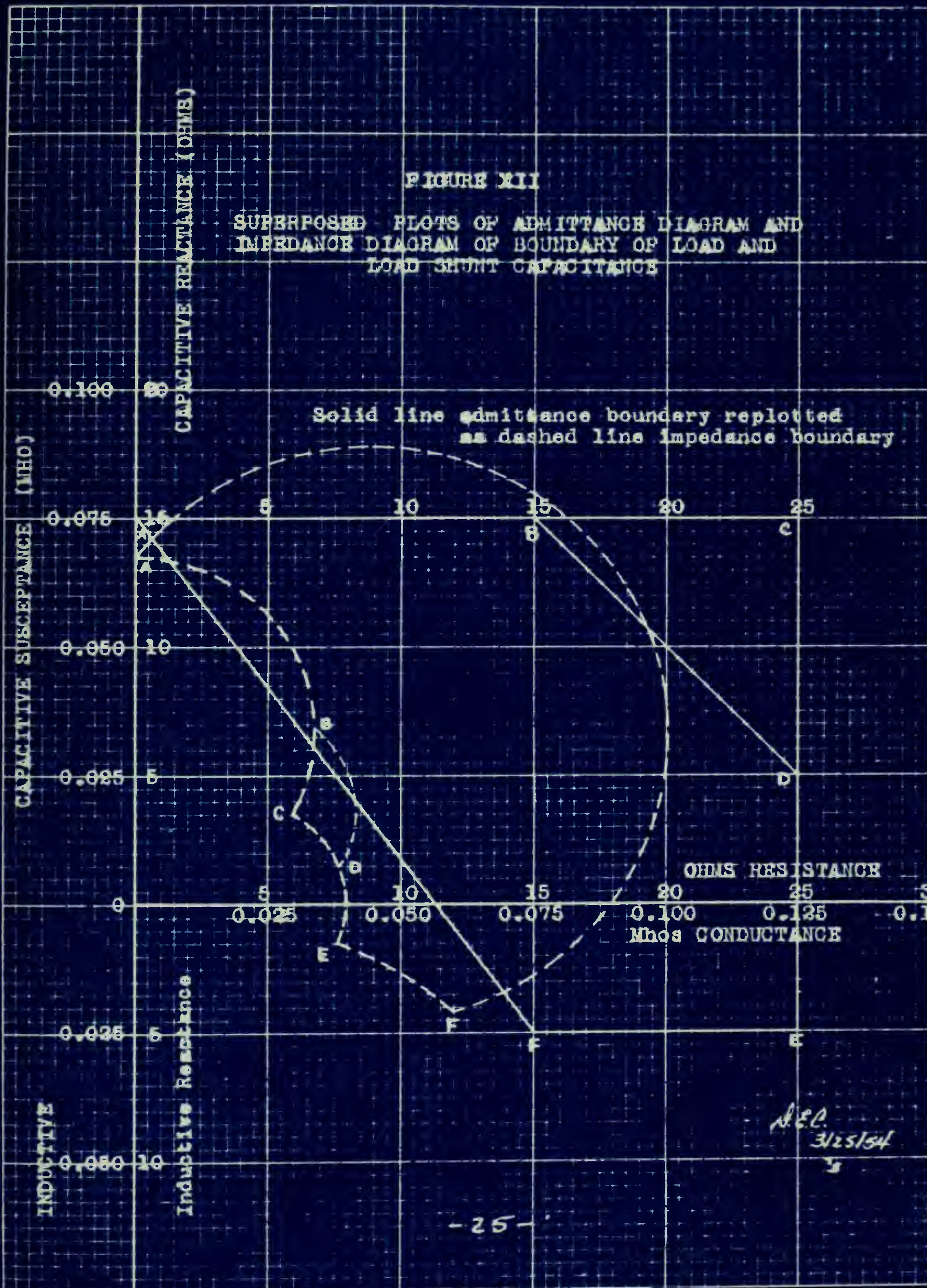


FIGURE XII
SUPERPOSED PLOTS OF ADMITTANCE DIAGRAM AND IMPEDANCE DIAGRAM OF BOUNDARY OF LOAD AND LOAD SHUNT CAPACITANCE
Solid line admittance boundary replotted as dashed line impedance boundary
CAPACITIVE SUSCEPTANCE (MHO)
CAPACITIVE REACTANCE (OHMS)
INDUCTIVE
Inductive Reactance
OHMS RESISTANCE
Mhos CONDUCTANCE
0.100
0.075
0.050
0.025
0
0.025
0.050
0.025
0.050
0.075
0.100
0.125
0.150
5
10
15
20
25
30
B
C
D
E
F
S.E.C.
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mined by the size of the capacitor shunted across the load. The range in terms of admittance indicated by the solid line was converted to a similar diagram in terms of impedance on this diagram. Consider the two points marked C. A line passing through these two points will also pass through the origin, and this line represents a condition of constant power factor. The admittance point C is about 1/7 mho from the origin, and the other point C is about 7 ohms from the origin. This fact can be checked visually by examining the diagram. The dashed contour was constructed by drawing a straight line from the origin to some point on the solid contour, measuring the distance from the origin to the solid contour in mhos, inverting the magnitude of the distance to obtain the impedance in ohms, and then laying this magnitude of impedance off on the same line to determine a point on the dashed line contour. This process is not so laborious as it might appear because each segment of the dashed line contour is a circular arc, and if the corresponding solid line is either horizontal or vertical, the center of the arc lies on the axis that is perpendicular to the line at a distance from the origin equal to half the reciprocal of the magnitude of the admittance at the intersection of the solid line and the axis. There are other tricks that can shorten this conformal mapping process. The solid line is a locus of admittance, and the dashed line is the same locus plotted against scales of resistance and reactance. A circle centered at the origin on this diagram represents a condition of constant admittance or impedance,

[illegible]

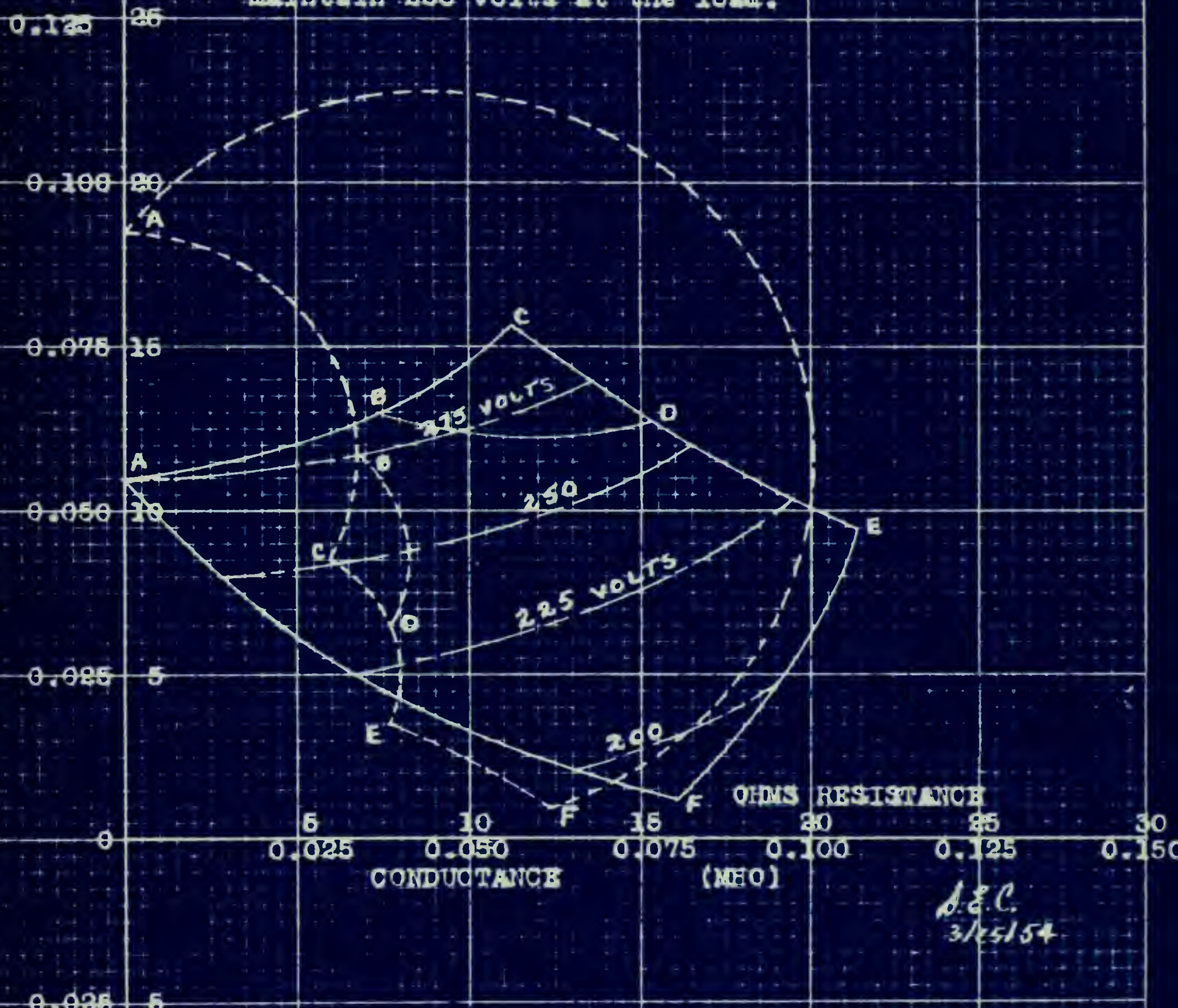
and if the voltage at the load terminals is constant, the circle is also a line of constant current through the series capacitor.

On Figure XIII the dashed impedance locus was replotted and shifted upward 5 ohms. The magnitude of the shift corresponds to the value of the series capacitor. In this case, the object was to maintain a constant voltage of 200 volts at the load within the load range, so it was assumed that the voltage anywhere within the area of load range on the previous diagram was 200 volts. The circular arcs of constant current through the series capacitor are centered at 0+j5 ohms and are applicable to points within the (dashed) impedance locus. The voltage at the generator terminal ahead of the series capacitor, for any point within the impedance locus, is equal to the load voltage, 200 volts, times the ratio of distances from the origin to the point and from the point to 0+j5. Lines of constant generator voltage within the impedance locus can be constructed. Then both the dashed locus and the lines of constant generator voltage can be mapped conformally into an admittance diagram. The solid locus is the new admittance locus, and the dashed lines within this locus represent conditions of constant generator voltage. The solid locus is the boundary of the original load range as viewed through a series capacitive reactance of 5 ohms and a shunt capacitive susceptance of 0.075 mho. The voltage lines indicate what the generator voltage must be to produce 200 volts at the load terminals.

FIGURE XIII

SUPERPOSED DIAGRAMS OF ADMITTANCE AND IMPEDANCE OF LOAD, LOAD SHUNT CAPACITOR, AND SERIES CAPACITOR

Impedance locus shifted upward by 5 ohms and replotted as admittance locus. Voltage arcs are noted as generator voltage necessary to maintain 200 volts at the load.



The shunt capacitor across the generator terminals can lower the generator characteristic to approximately superpose the voltage lines on this diagram, Figure XIII. When the voltage lines on this diagram have the same slope and spacing as the arcs of constant voltage on the generator voltage map, a solution has been achieved. An exact solution is not possible, since the higher voltage lines are more widely spaced than the lower voltage lines on the generator voltage map, but the higher voltage lines must be more closely spaced than the lower voltage lines for this coupling network of three capacitors in a pi configuration. This situation is inherent in the generator and coupling network electrical characteristics, although, it is possible that some alteration to the coupling network in the form of an additional element could overcome this difficulty. It is not obvious that this exact solution cannot be achieved. The spacing of the generator voltage lines depends upon the generator magnetization curve. The spacing of voltage lines on a diagram similar to Figure XIII depends upon the fact that the ratio of the distance to the origin to the distance to a point near the origin becomes smaller as the reference point under consideration moves away from the origin, and that points far from the origin on the impedance diagram plot close to the origin on the admittance diagram. An exact solution is not possible, but the configuration of Figure XIII has just about the same spacing and slope of voltage arcs as the generator characteristic, and this is the best result of four trial solutions. This

determines the optimum parameters for the pi network.

To determine what results can be achieved with this optimum solution, it is necessary to start with the experimentally determined generator terminal characteristic, Figure XIX in Chapter III. The generator characteristic was shifted downward until the 200-volt arc passed through the origin, then the voltage arcs were mapped conformally into an impedance diagram, and the impedance loci of constant generator voltage were shifted downward 5 ohms to accounts for the series capacitor. The dashed lines on Figure XV represent the result of this plotting. The dashed lines on this figure were remapped conformally into the solid curves of admittance loci of constant generator voltage. Since the generator voltage was known at every point on these lines and corresponding impedances of the load were known, the load voltage was determined at any point on the solid lines by using the same mapping procedure as before. By passing lines through the points of equal load voltage, the voltage map of Figure XVI was obtained. On this map, the solid lines represent conditions of constant load voltage. A load range is drawn on the map in a favorable position. It is now possible to see what the load voltage and generator voltage will be for any load admittance.

This mapping process may appear to be very involved, but anyone doing the mapping will quickly become quite sophisticated in his approach to the process. In this case, the mapping process is nothing more than a graphical means of applying linear circuit analysis to a non-linear element, the induction generator.

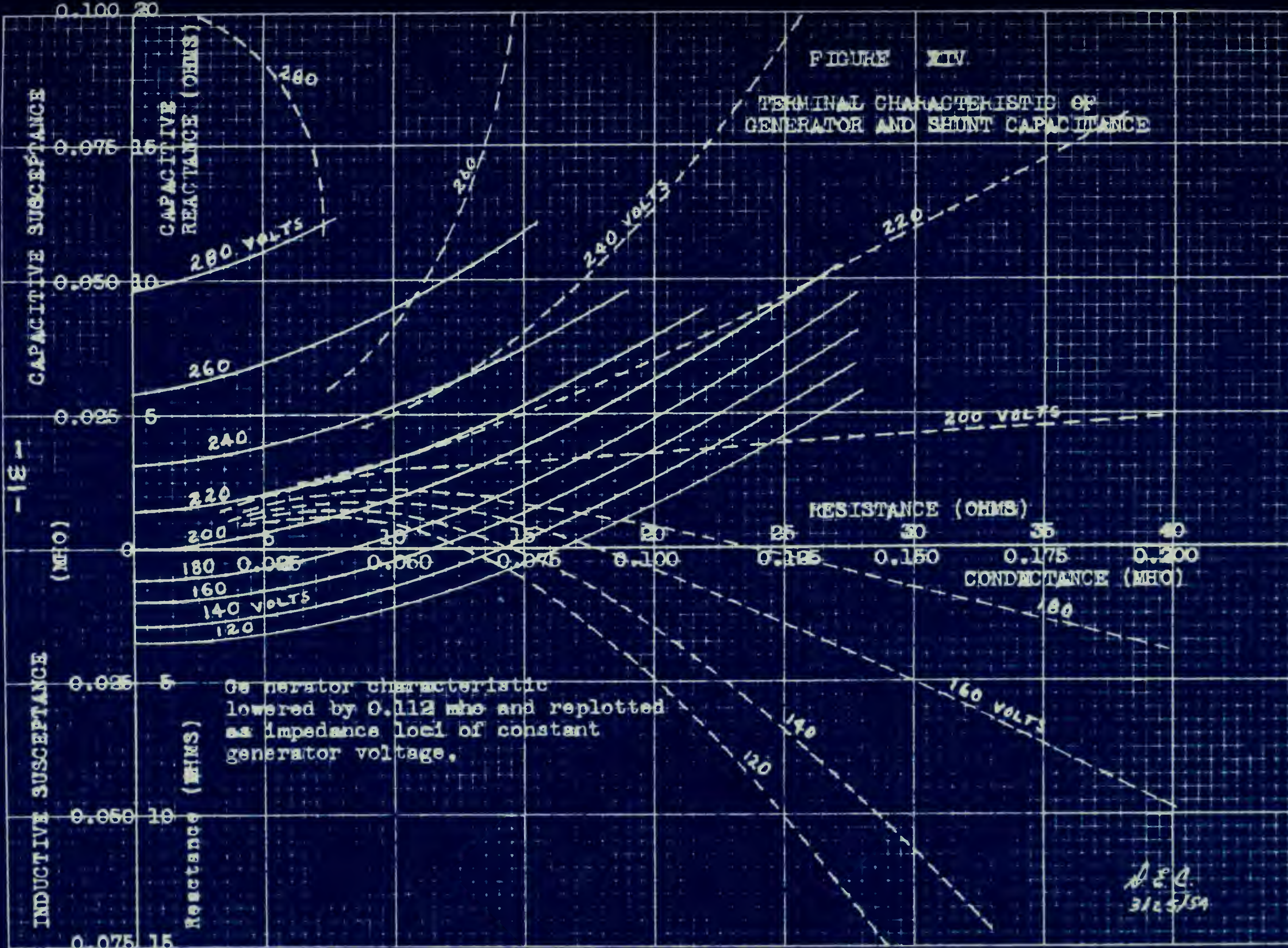


FIGURE XIV
TERMINAL CHARACTERISTIC OF GENERATOR AND SHUNT CAPACITANCE
CAPACITIVE SUSCEPTANCE
CAPACITIVE REACTANCE (OHMS)
INDUCTIVE SUSCEPTANCE
Reactance (OHMS)
(MHO)
0.100
0.075
0.050
0.025
0
0.025
0.050
0.075
20
15
10
5
5
10
15
RESISTANCE (OHMS)
5
10
15
20
25
30
35
40
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
CONDUCTANCE (MHO)
280 VOLTS
260
240
220
200
180
160
140 VOLTS
120
280
260
240 VOLTS
220
200 VOLTS
180
160 VOLTS
140
120
Generator characteristic lowered by 0.112 mho and replotted as impedance loci of constant generator voltage.
3/25/54

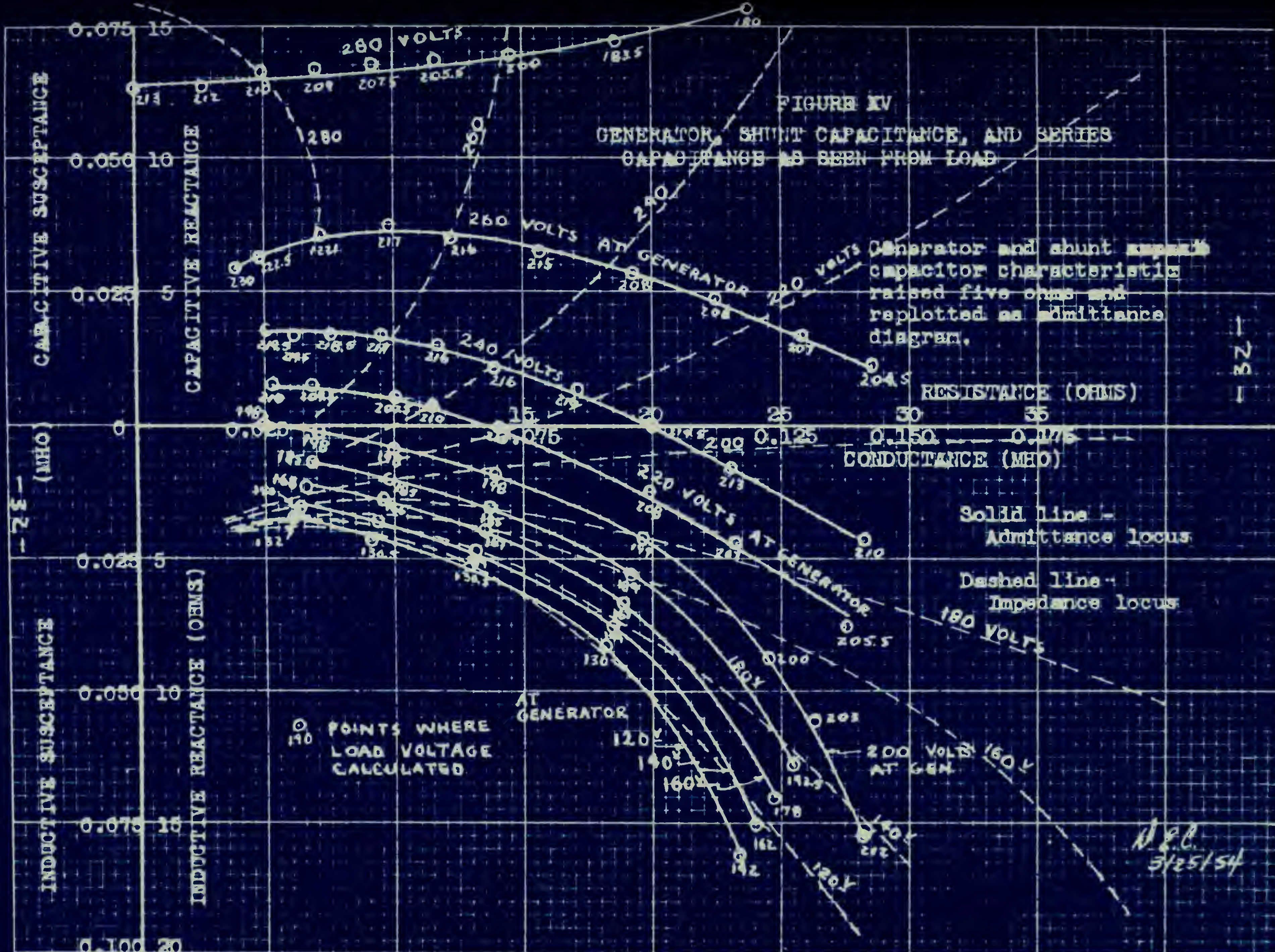
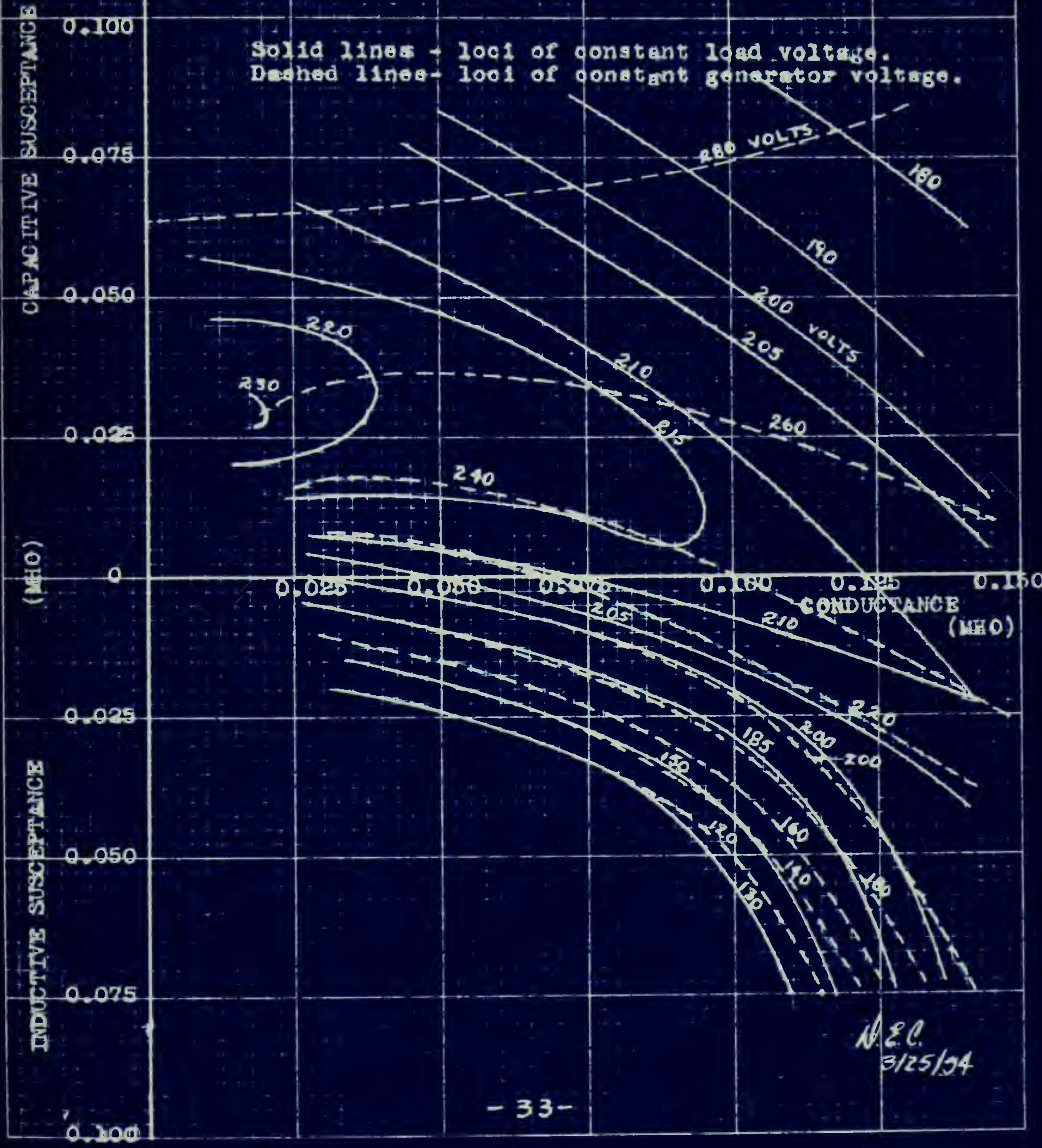


FIGURE XV
GENERATOR, SHUNT CAPACITANCE, AND SERIES CAPACITANCE AS SEEN FROM LOAD
Generator and shunt capacitor characteristic raised five ohms and replotted as admittance diagram.
RESISTANCE (OHMS)
CONDUCTANCE (MHO)
Solid line - Admittance locus
Dashed line - Impedance locus
CAPACITIVE SUSCEPTANCE
CAPACITIVE REACTANCE
INDUCTIVE SUSCEPTANCE
INDUCTIVE REACTANCE (OHMS)
(MHO)
280 VOLTS
260 VOLTS AT GENERATOR
240 VOLTS
220 VOLTS AT GENERATOR
180 VOLTS
200 VOLTS AT GEN.
AT GENERATOR
POINTS WHERE LOAD VOLTAGE CALCULATED
N.E.C. 3/25/54

FIGURE XVI

PREDICTED VOLTAGE MAP OF GENERATOR AND LOAD VOLTAGES WITH OPTIMUM PI NETWORK COUPLING PLOTTED ON SCALES OF ADMITTANCE OF LOAD AND LOAD SHUNT CAPACITOR



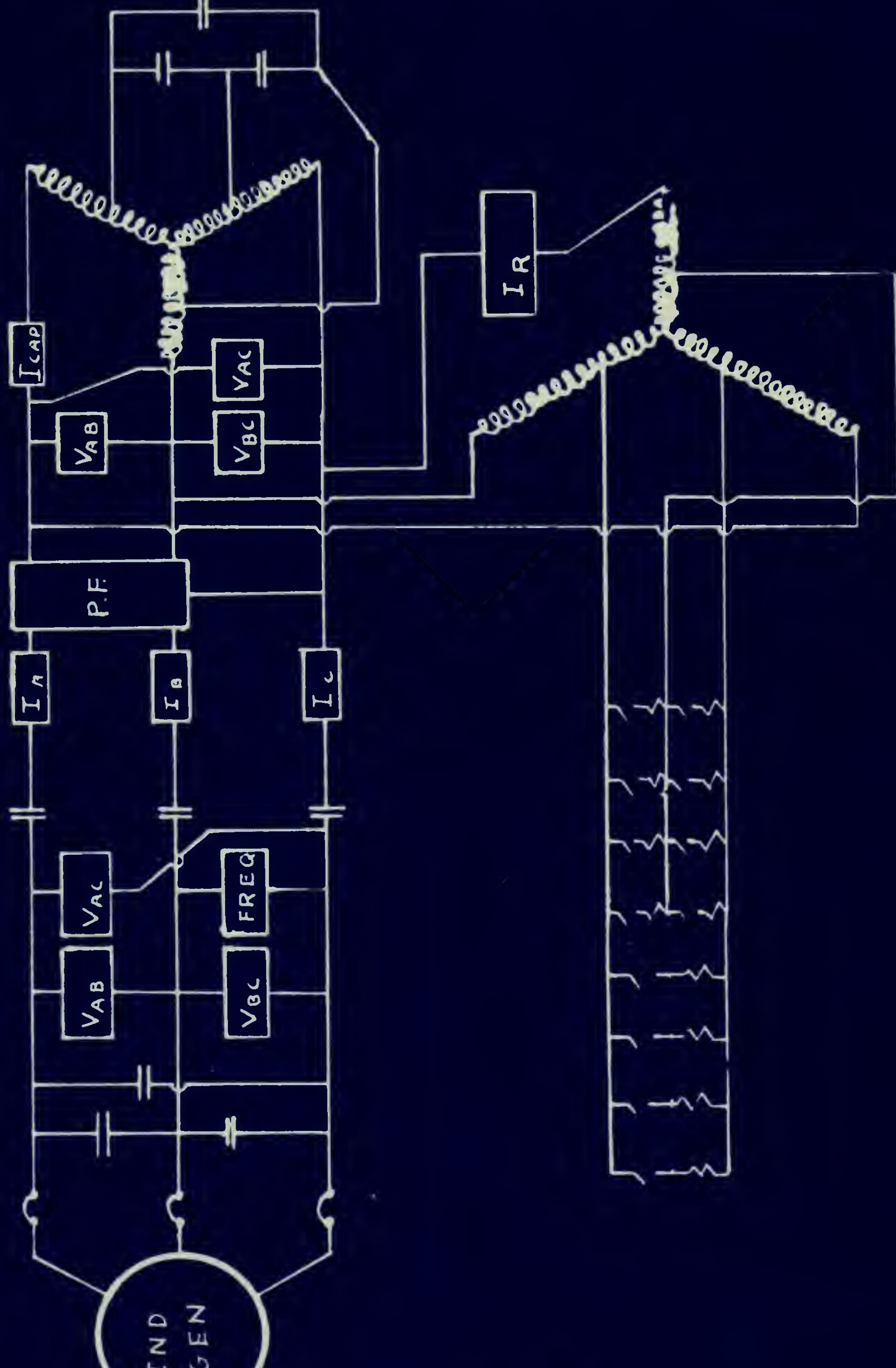
2.3.4 Laboratory Procedure

Test circuit No. 4, Figure XVII, was used to obtain the voltage map experimentally, in order to verify the techniques described above. In this test circuit, the load and shunt capacitance across the load were represented by resistor and capacitor banks connected through three phase variacs, these variacs providing for continous variation of the components of load admittance without disturbing the balance of the three phases. The load was coupled to the generator by means of a series capacitor and a shunt capacitor. The following data was measured with ordinary laboratory instruments which are accurate to 1% of full scale: generator voltage, line current, load voltage, load current, shunt capacitor current across the load, load power factor, frequency, and the D-C motor current, voltage and speed. To facilitate correlation of the data, runs were made with constant load conductance for a group of values of load susceptance. Data was taken for 94 points on the voltage map.

The shunt capacitance and the series capacitance were adjusted to be the same as the values used for the conformal mapping described in the previous section. This will be explained to emphasize the exact meaning of the admittance scales on the diagrams. The series capacitors were connected in wye and were set, therefore, at five ohms since the impedance map had been shifted five ohms. If the series capacitance had been delta-connected, they would have been set at 5/3 ohms. The capacitors shunted across the generator terminals had to shift

FIGURE XVII

TEST CIRCUIT NO. 4



the 200-volt voltage arc down until it passed through the origin. Since this arc intersected the susceptance axis at 0.1122 mhos, the shunt capacitors were set at 0.0374 mhos per phase. All the capacitors and resistors in the banks had previously been calibrated in mhos at 60 cycles per second. For this test, the calibration was checked with a voltmeter and an ammeter, taking each bank representing a single circuit element as a unit.

The factor limiting the extent of the test was, as in all other tests, the power limit of the D-C driving motor.

2.4 Work on Other Problems

No other ideas were developed completely enough to be subjected to serious laboratory testing, but some work was done on other problems associated with developing a satisfactory voltage regulator. Since this thesis is at least the fifth, and probably not the last, devoted to this particular problem, some of the work done on other problems will be reported here briefly for the aid of later workers.

It was planned originally to connect three direct-current-controlled saturable reactors in parallel with the capacitors across the generator terminals, to provide an adjustable capacitance in this branch as required to maintain a constant load voltage by means of the controllable reactor. Twelve 90-var three-legged reactors were available for this purpose. These reactors were actually connected into test circuit No. 4 in parallel with B_{c1}. They were delta-connected so that the third, sixth, ninth, twelfth, etc., harmonic currents would

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

flow only in the reactor windings. The four reactors in each phase were used in parallel groups of two, in series with another group in each phase. The A-C windings in each parallel group were connected in series to eliminate all even harmonic currents. This series connection also provides the fastest response time. Theoretically, this connection also prevents all harmonics except the fifth, seventh, eleventh, thirteenth, seventeenth, nineteenth, etc., from appearing outside the reactor windings (26, 27, and 28). A six-volt dry cell battery was connected to the D-C winding of this configuration through a rheostat, and an attempt was made to control the load voltage manually with this rheostat.

It was also planned to control the D-C current controlling the saturable reactor operation by means of an automatic voltage regulator feedback loop, responding to the load voltage at the load. An ancient voltage regulator was available in the laboratory, and this regulator was put into working order. However, it was found to have the inverse of the desired characteristic, so a means of inverting its characteristic was worked out. Manual control has been found unsatisfactory, so the automatic regulator elements were never tested in the completed system.

Chapter III

RESULTS

3.1 Induction Generator Terminal Characteristics

The results of the first test are presented on two diagrams. On Figure XVIII, the observed values of generator terminal voltage are plotted against load capacitive susceptance (or generator inductive susceptance). Solid lines are faired through the data points with each of the five solid lines corresponding to a particular value of load conductance. The dashed line was obtained by extrapolation to a condition of zero conductance, which could not be observed because of the extraneous conductance of meters, capacitors, variac windings, and connections. This diagram completely describes the generator electrical terminal characteristics, but it is not the most convenient form. This intermediate diagram is required to correlate the data because it is not possible to exactly balance the three phases nor to obtain the readings at exactly the desired voltages.

Figure XIX was obtained by plotting data taken from Figure XVIII. This new diagram is the admittance-diagram voltage map, the most useful description of the steady state generator operating characteristics. At any point on this map, the voltage, conductance, and susceptance are known; therefore the current, admittance, real power, reactive power, and other quantities can be calculated. Any straight line passing through the origin on this diagram is a locus of constant power factor, and any circle centered at the origin is a locus of constant admittance.

[illegible]

[illegible]

[illegible]

[illegible]

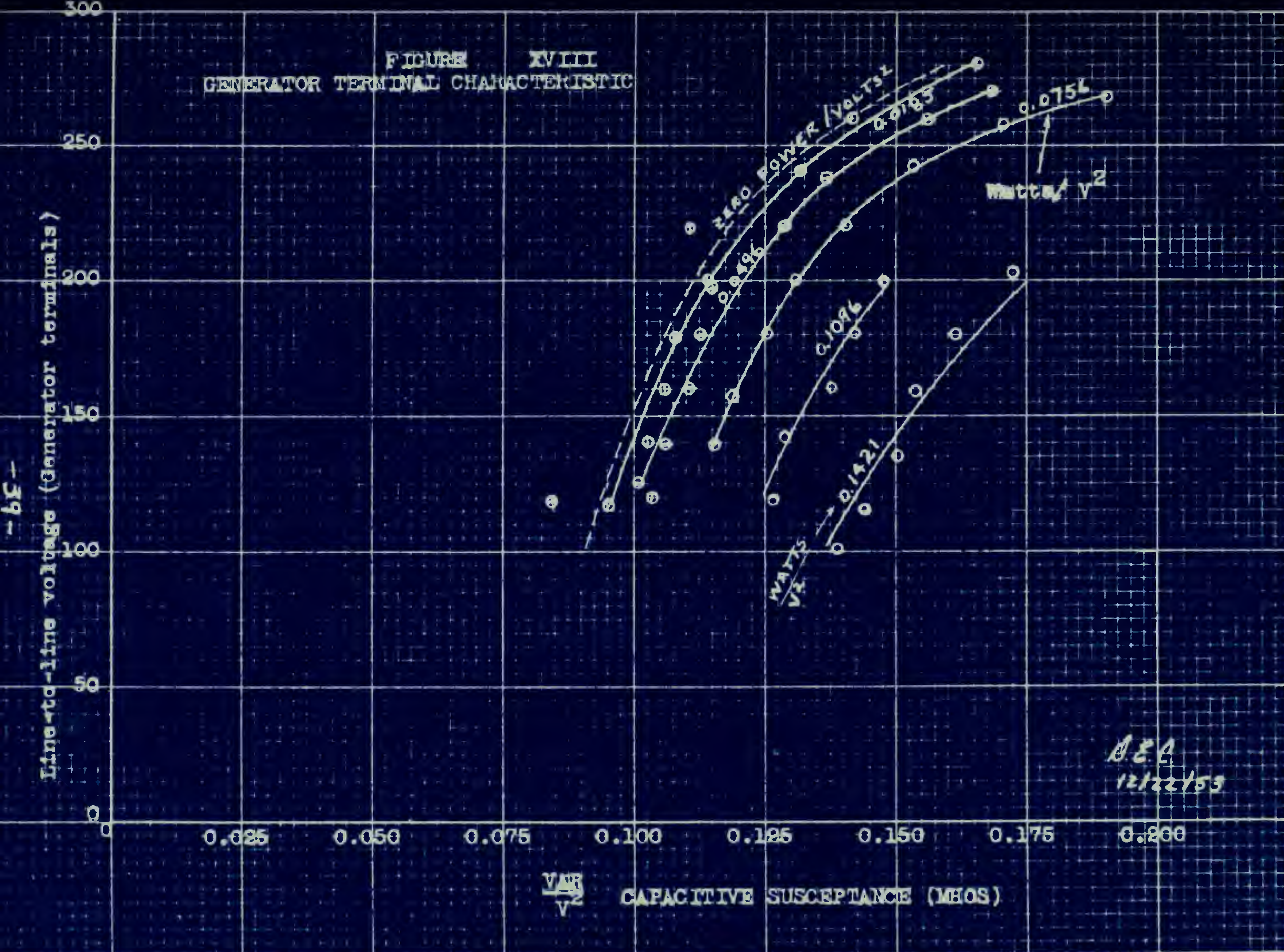
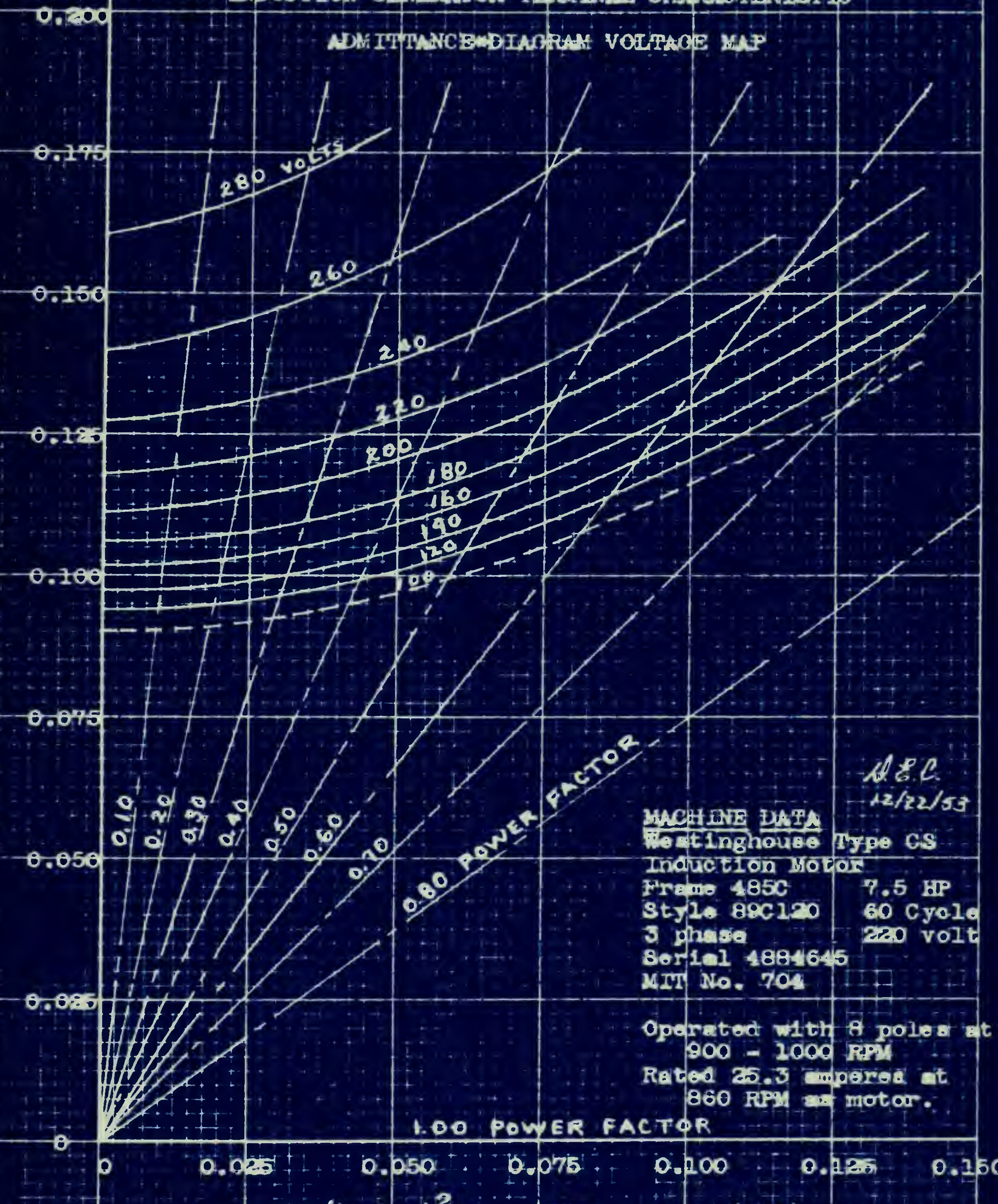


FIGURE XVIII
GENERATOR TERMINAL CHARACTERISTIC
Line-to-line voltage (Generator terminals)
300
250
200
150
100
50
0
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
VAR/V2 CAPACITIVE SUSCEPTANCE (MHOS)
ZERO POWER
0.0183
0.0496
0.1096
0.1421
0.075L
Watts/V2
WATTS/V2
12/22/53

FIGURE XIX

INDUCTION GENERATOR TERMINAL CHARACTERISTIC

ADMITTANCE DIAGRAM VOLTAGE MAP



3.2 Series Capacitor Coupling

3.2.1 Voltage Regulation With Transformers and Balanced Load

The following table is a summary of results obtained with a gamma network with transformers coupling a unity power factor load to the generator as shown on the diagram of test circuit No. 2, Figure V. Load voltage is tabulated versus load conductance. Overvoltage is the maximum observed voltage minus the open-circuit voltage, and undervoltage is equal to the open-circuit voltage minus the minimum observed voltage. The range of voltage is the sum of the overvoltage and the undervoltage, and the voltage variation is the range of voltage expressed as a percentage of the open-circuit voltage. It is apparent from the table why the ordinary definition of voltage regulation has no significance. For instance, the voltage regulation computed for run 11 is

$$(180.5 - 179.5)/179.5 = 0.56\%.$$

Table I

Voltage Regulation for a Variable Unity Power Factor Load Couples by a Gamma Network With Transformers

Load Conductance (mho)	Run 6 Load Volts	Run 7 Load Volts	Run 8 Load Volts
open-circuit	149	156	156
0.0333	142	140	132.2
0.0666	167	157	143.5
0.1000	189	186	164
Overvoltage	40	30	8
Undervoltage	7	16	23.8
Range of Voltage	47	46	31.8
Voltage Variation	31.5%	28.8%	20.5%
Susceptance of Series Capacitor (mho)	0.0489	0.0610	0.0758

[illegible]

Table I continued

Load Conductance (mho)	Run 11 Load Volts	Run 12 Load Volts	Run 14 Load Volts
open-circuit	180.5	181	214.3
0.0333	164.5	169.3	197.7
0.0666	167	183.7	187
0.1000	179.5	194.7	203
Overvoltage	--	13.7	--
Undervoltage	16	11.7	27.3
Range of Voltage	16	25.4	27.3
Voltage Variation	8.3%	14.1%	12.7%
Susceptance of Series Capacitor (mho)	0.0758	0.0595	0.0510

Figure XX is a plot of the generator voltage, series capacitor voltage, and load voltage for run 12. The changes of the three voltages with load is typical of the runs tabulated above.

Runs 9 and 13 differed from those listed above in that the voltage across the resistor in one phase suddenly dropped to about 25 volts and the greater part of the generator terminal voltage appeared across the transformer and capacitor combination when the full load conductance was switched on. The other two phases behaved normally. For one run an added 0.0111 mho was switched into each phase and a second phase exhibited a sudden drop in load voltage. It was reasoned that the series capacitor connected to the secondary and the magnetizing susceptance of the transformer had become resonant and that the combination appeared in the line as a blocking impedance. An additional ammeter was inserted into the circuit, as illustrated in Figure V, to measure the current circulating through the capacitor and the secondary

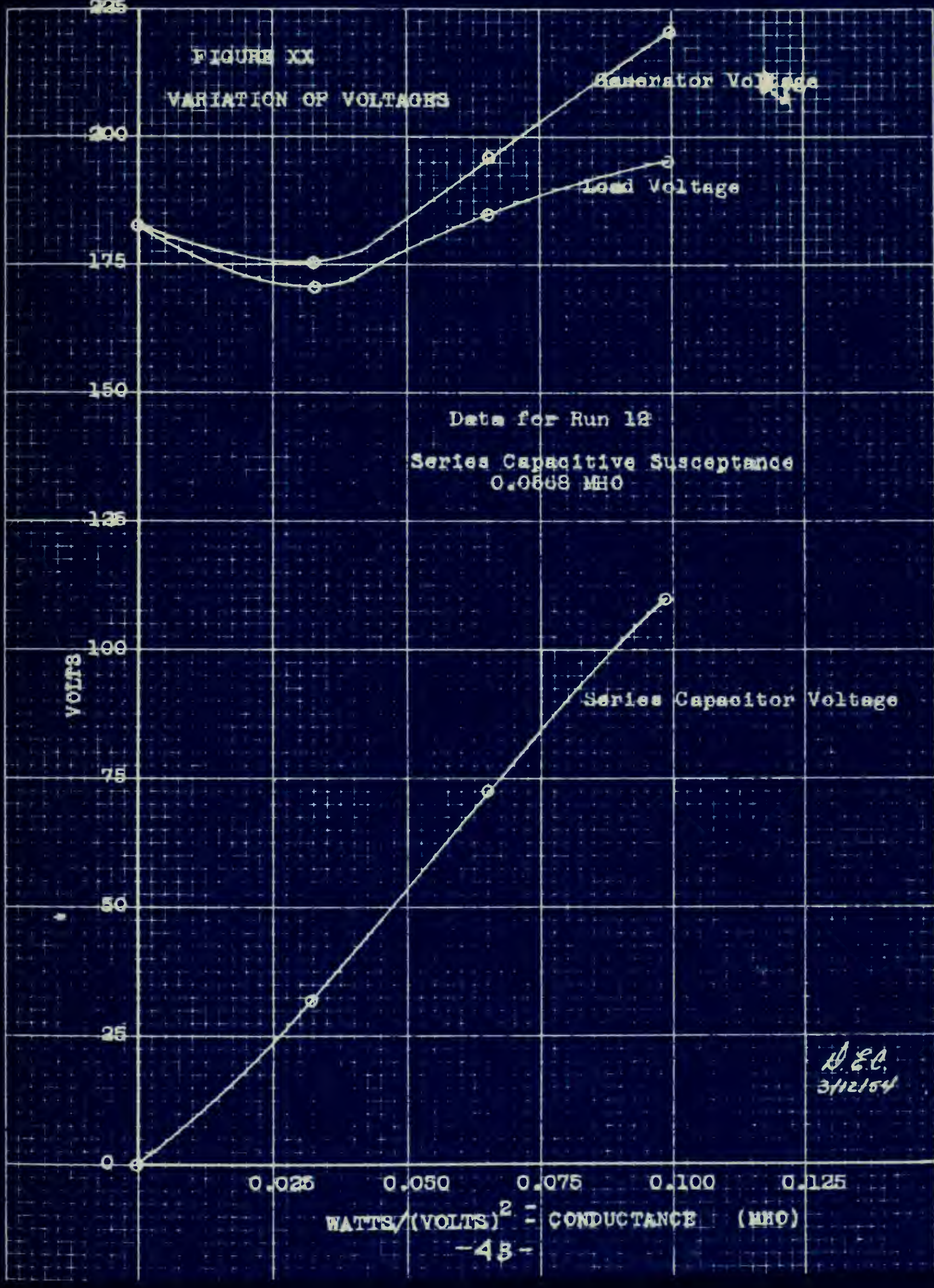


FIGURE XX
VARIATION OF VOLTAGES
Generator Voltage
Load Voltage
Data for Run 12
Series Capacitive Susceptance
0.0868 MHO
Series Capacitor Voltage
VOLTS
225
200
175
150
125
100
75
50
25
0
0.025
0.050
0.075
0.100
0.125
WATTS/(VOLTS)² = CONDUCTANCE (MHO)
D.E.C.
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winding. The ratio of primary current to secondary current changed from 4:1 in normal operation to 1:2 when resonance occurred.

3.2.2 Voltage Regulation Without Transformers

Table II reports the same sort of information as Table I above. The data for Table II was obtained with test circuit no. 3, Figure VI.

Table II

Voltage Regulation for Variable Unity Power Factor Load Couples by a Gamma Network Without Transformers

Total Conductance (mho)	Run 15 Load Volts	Run 16 Load Volts	Run 17 Load Volts	Run 18 Load Volts
open-circuit	188	184.5	186	187
0.0333	180.3	179.2	176.5	175
0.0666	194.3	190	186	182.5
0.1000	205.7	202	199	196.7
Overvoltage	17.7	17.2	13	9.7
Undervoltage	7.7	5.6	9.5	12
Range of Voltage	25.4	22.8	22.5	21.7
Voltage Variation	13.5%	12.3%	12.5%	11.8%
Susceptance of Series Capacitor (mho)	0.0715	0.0811	0.0838	0.0920

The magnitude of the susceptance of the series capacitor is the diameter of the semicircular locus of load admittance as viewed from the generator through the coupling network. (See Figure III.) The size of the shunt capacitor controls only the open-circuit voltage. As the series suspectance increases, the overvoltage decreases and the undervoltage increases.

3.2.3 Load Unbalance and Lack of Frequency Control

A summary of the data for runs with unbalanced load and

without frequency control is reported in Appendix C-3(c). With the load unbalanced, the voltage in the lightly loaded phases tends to rise so that the average voltage of the three phases tends to rise slightly (13.6 volts at most). The voltage in the heavily loaded phase or phases was steadier than with balanced loads.

Without frequency control, the generator speed and voltage decreased with load. The successive voltages across the resistors, as the load was added in increments of 0.0111 mho per phase, were 188, 154, 154, 164.7, and 172 volts, and the frequencies were 60.00, 59.12, 58.25, 57.08, and 56.02 cycles per second. The generator speed dropped from 920 rpm to 878 rpm, 4.6%, while the frequency decreased 6.6%.

3.2.4 <u>Short-Circuit Test Results</u>

Selective switching was obtained from all initial operating conditons with both three-phase and single-phase short circuits. One of the smaller circuit breakers sometimes would not open as rapidly as the larger breakers, so this breaker was rotated among the phases and a number of tests were conducted at random times to eliminate the possibility that the effect might be due to some cause other than a reluctant breaker. After the series capacitors were switched out by the circuit breakers, they remained highly charged. When the small breaker set at 15 to 25 amperes failed to operate, the larger backup breaker set at 90 amperes was actuated by the short-circuit current.

3.3 Fixed Element Regulation

Figures XXI through XXIX inclusive are plots of the data obtained with fixed shunt and series capacitors. Each of these plots shows the variation of generator and load voltage with changes in load susceptance for a fixed value of load conductance. The data from these plots are replotted as

XXX
admittance-diagram voltage maps in Figures XXXI and Figure
XXXII

XXX is a generator voltage map and Figure XXXI is a load voltage map. The susceptance and conductance scales on both diagrams are calibrated in mhos of admittance at the terminals preceding the capacitor shunted across the load. In order to interpret these diagrams in terms of load admittance it is necessary to realize that the shunt capacitor raises the load range. If no capacitors were shunted across the load, the unity power factor line would coincide with the horizontal axis. If a total capacitance equivalent to 0.075 mho were divided into 0.025 mho per phase and shunted across the load, any unity power factor load would lie somewhere on a horizontal line parallel to the horizontal axis and intersecting the vertical axis at 0.075 mho, and any inductive load would lie somewhere below this line.

3.4 Manual Control of Load Voltage

With the system operating at a conditon approximately in the center of the maps described above, the effective value of the generator shunt capacitors was reduced about 0.015 mho per phase by means of saturable reactors with the d-c current being manually controlled. This was the maximum

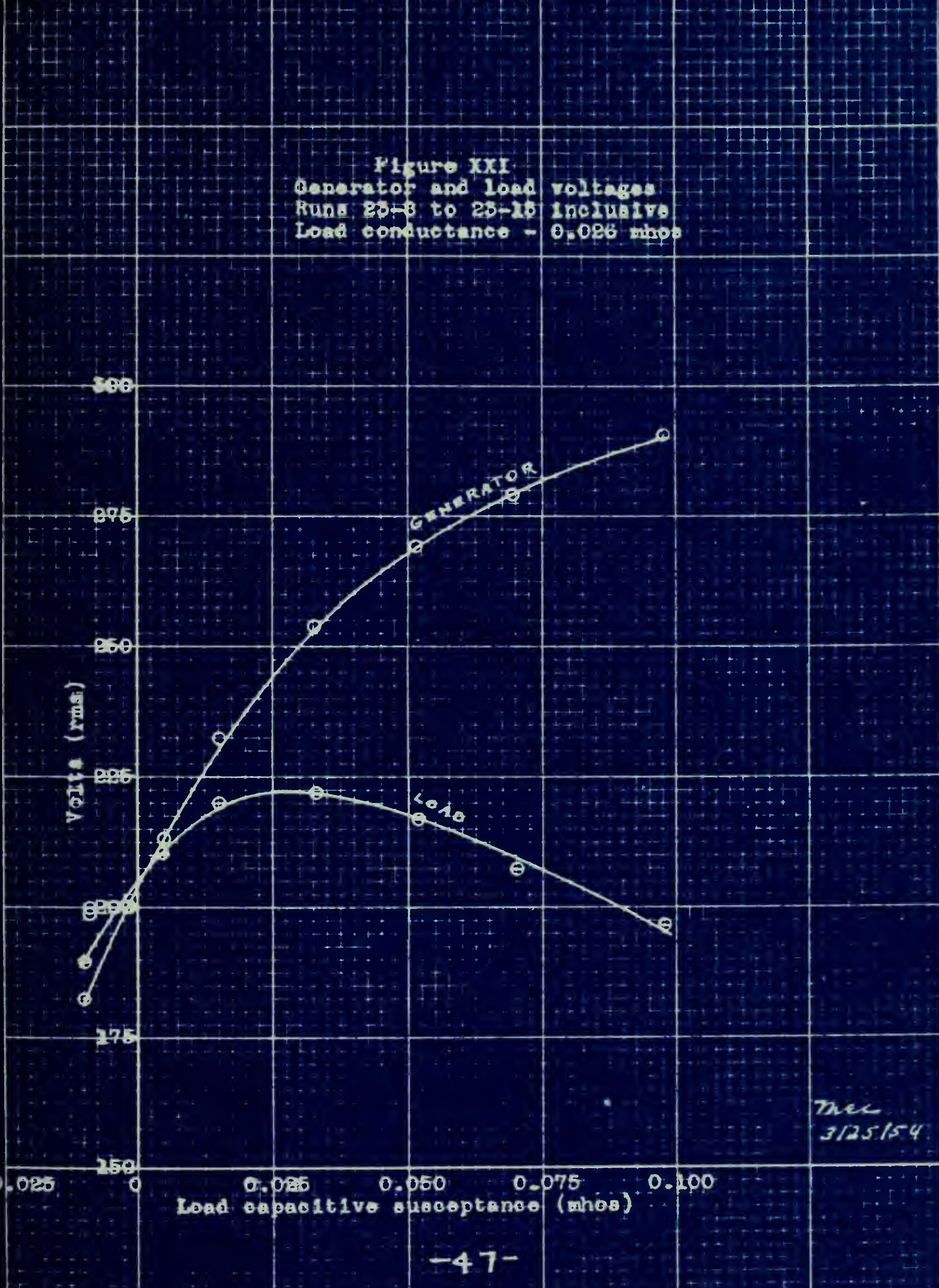


Figure XXI
Generator and load voltages
Runs 23-8 to 23-16 inclusive
Load conductance - 0.026 mhos

Figure XXXII
Generator and load voltages
Runs 23-1[illegible] to 23-[illegible] inclusive
Load conductance - 0.00[illegible] mho

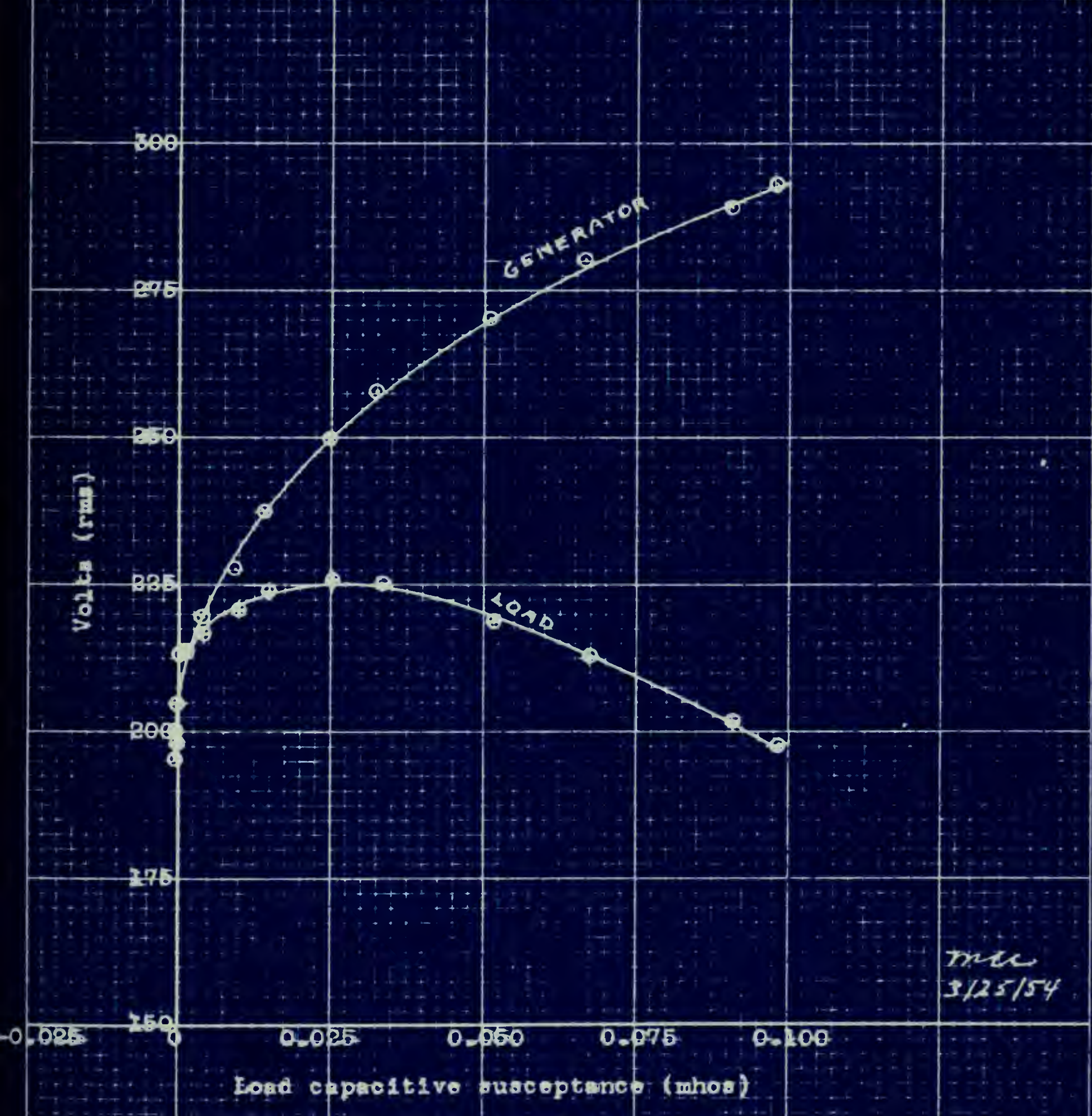
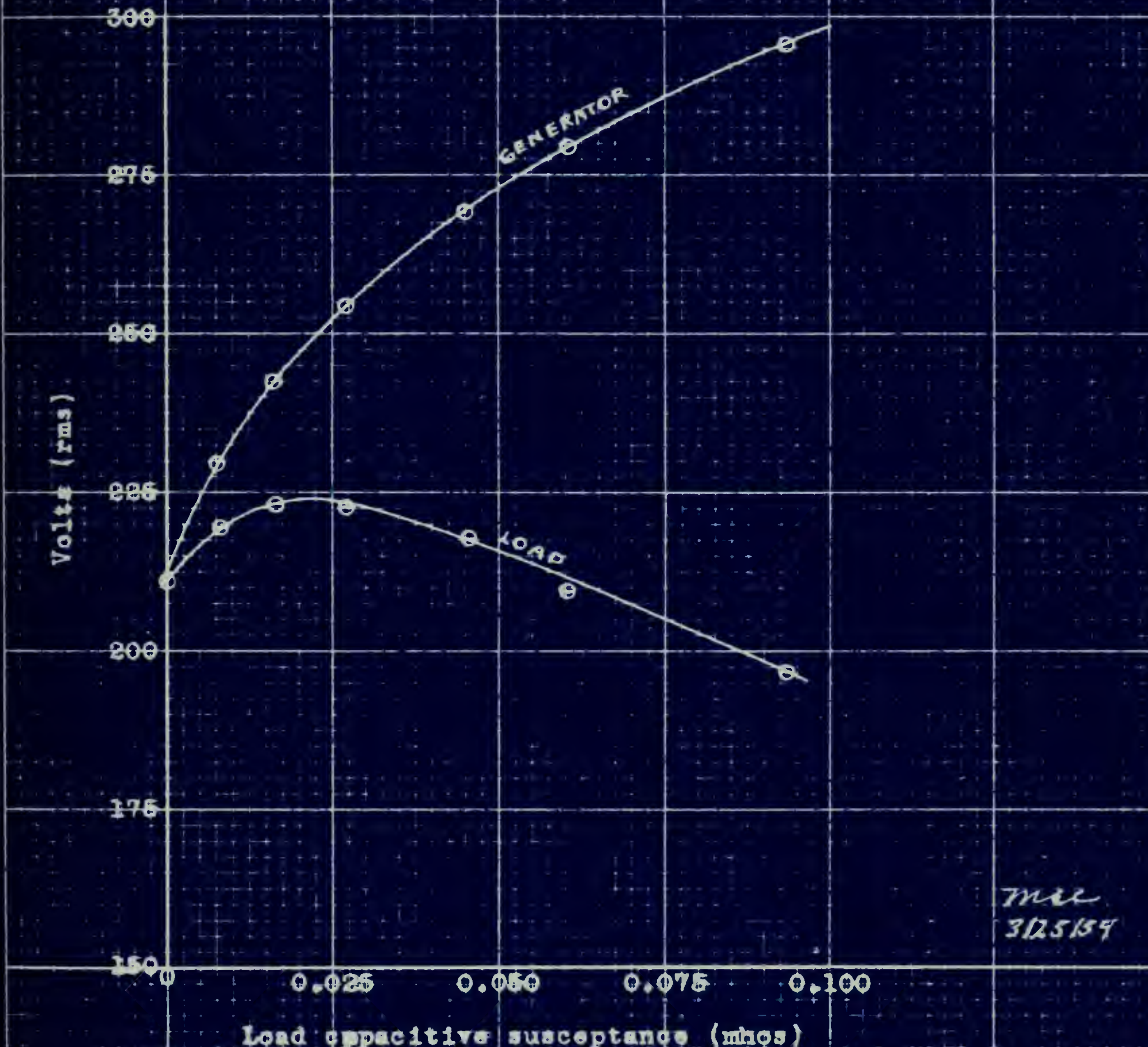


Figure XXIII
Generator and load voltages
Runs 23-29 to 23-37 inclusive
Load conductance - 0.015 mho



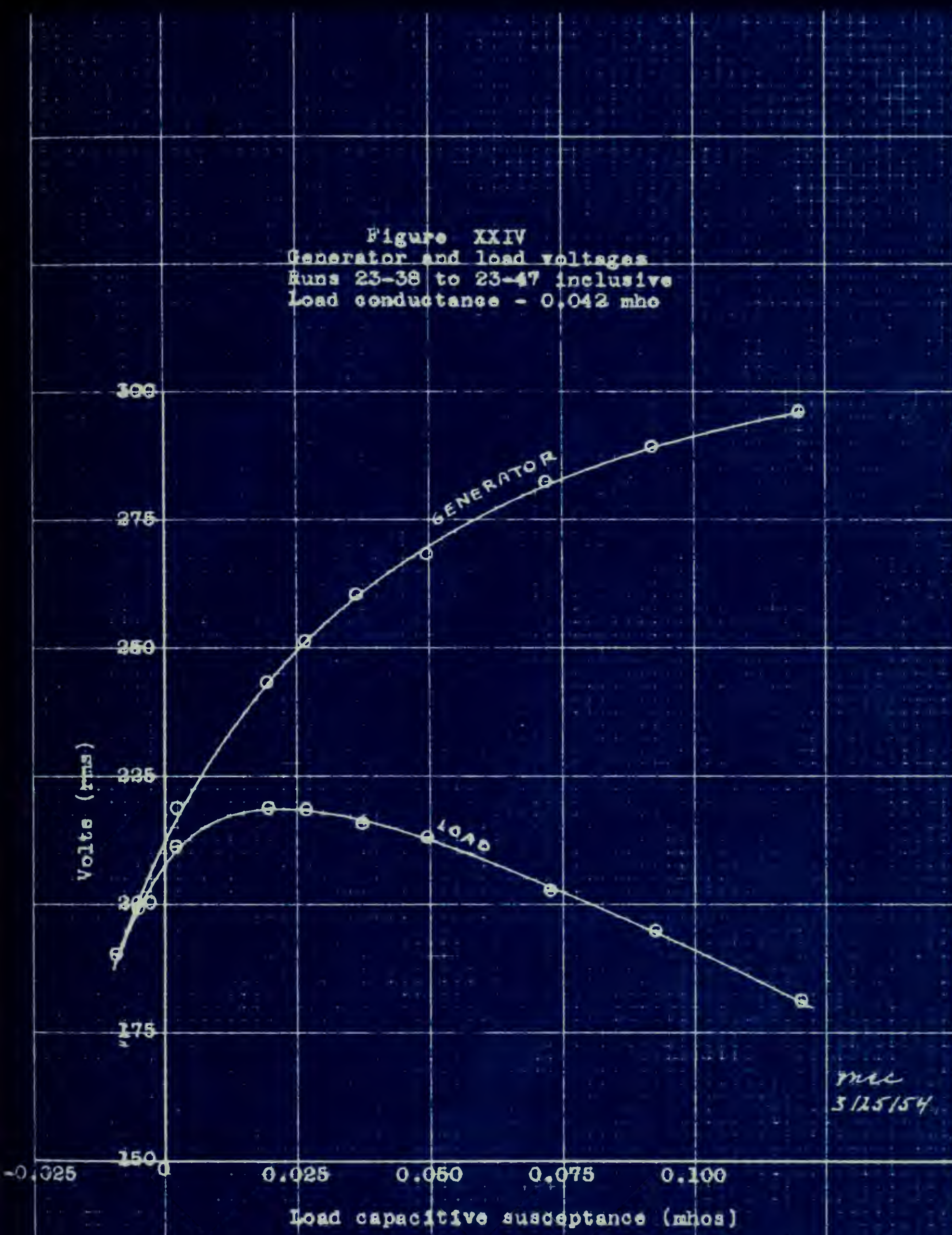


Figure XXIV
Generator and load voltages
Runs 23-38 to 23-47 inclusive
Load conductance - 0.042 mho
300
275
250
225
200
175
150
Volts (rms)
GENERATOR
LOAD
-0.025
0
0.025
0.050
0.075
0.100
Load capacitive susceptance (mhos)
mec
3/25/54

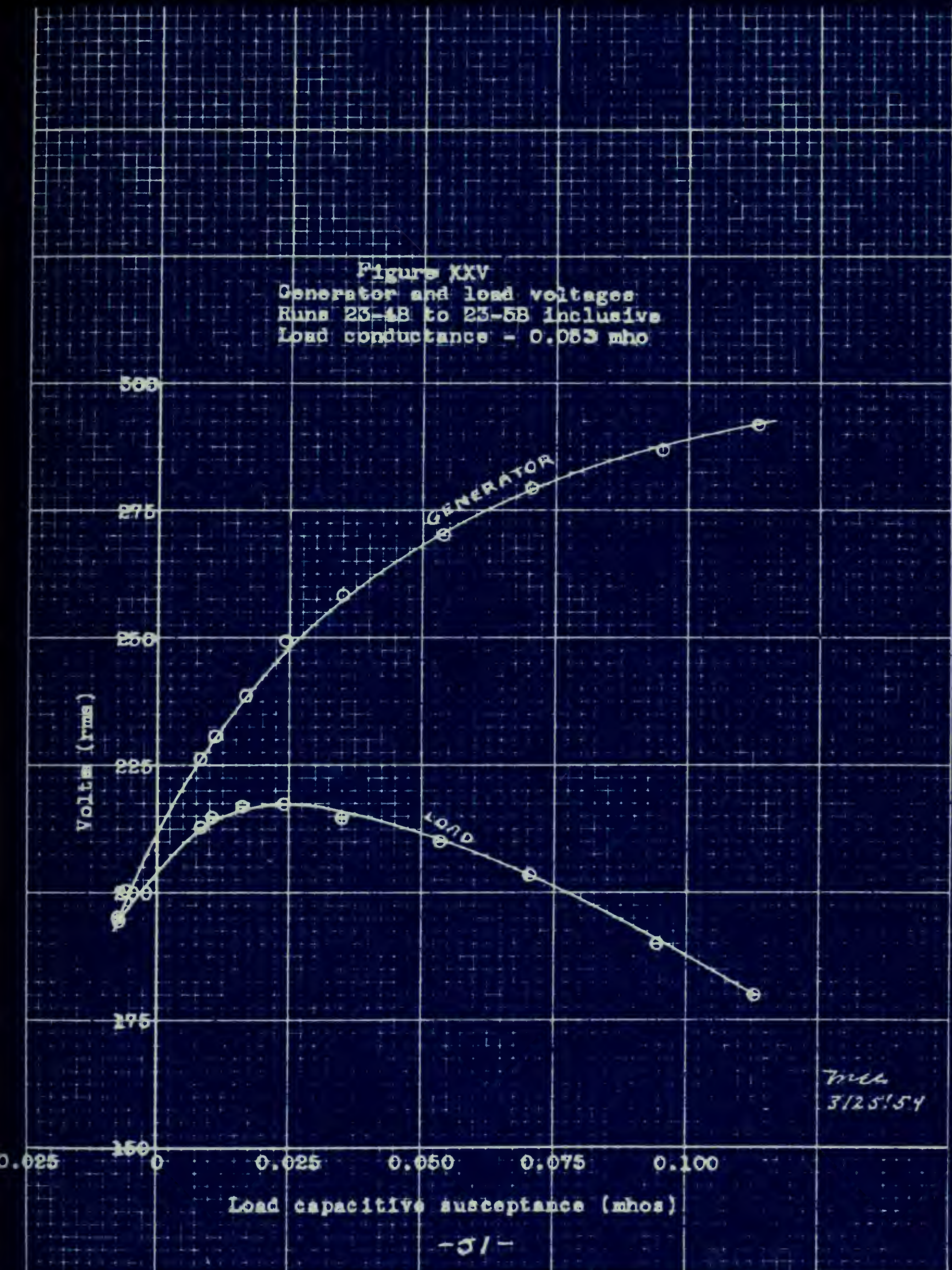


Figure XXV
Generator and load voltages
Runs 23-48 to 23-58 inclusive
Load conductance - 0.053 mho

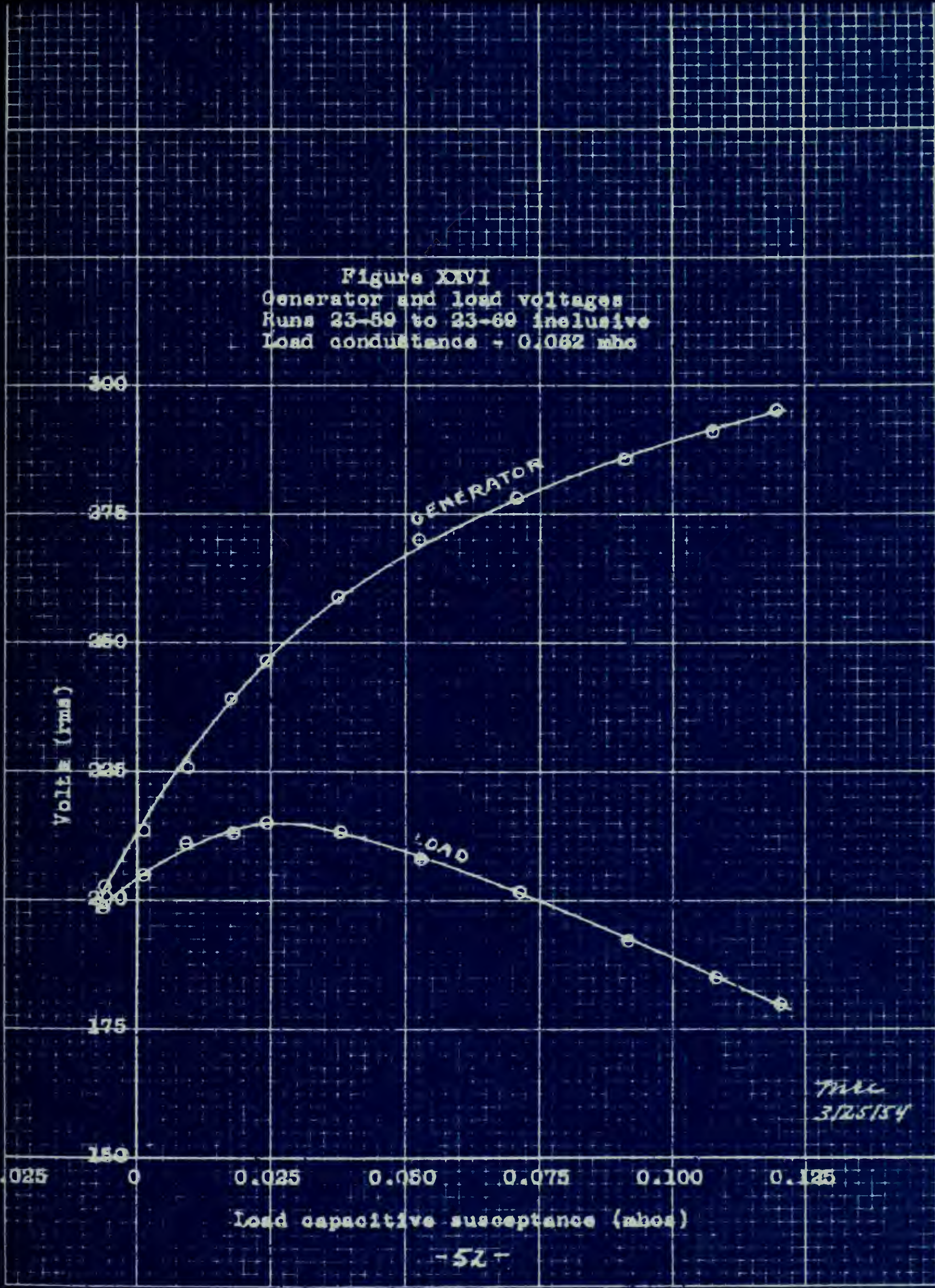


Figure XXVI
Generator and load voltages
Runs 23-59 to 23-69 inclusive
Load conductance - 0.062 mho

Figure XXVII
Generator and load voltages
Runs 23-70 to 23-78 inclusive
Load conductance - 0.069 mho

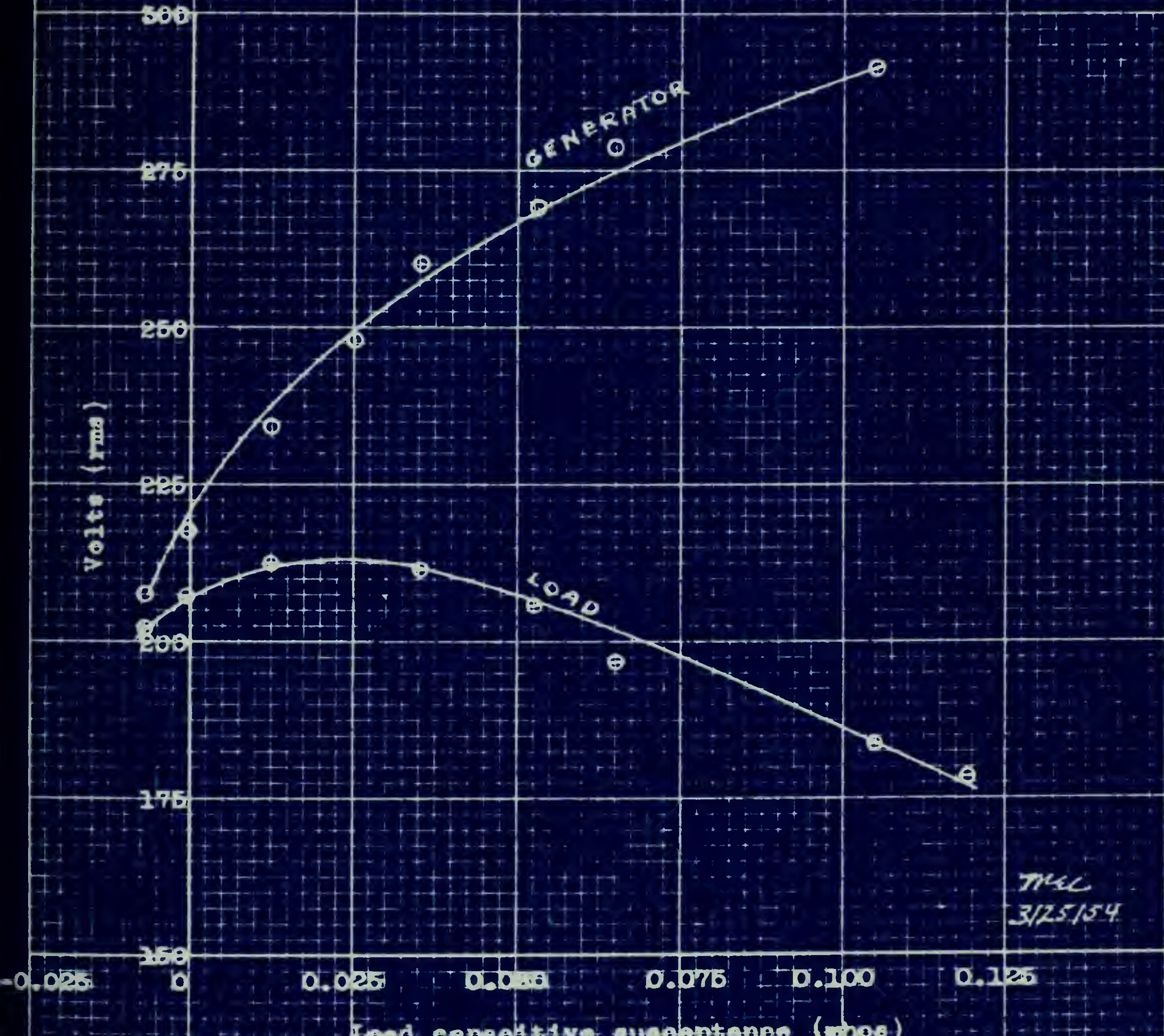
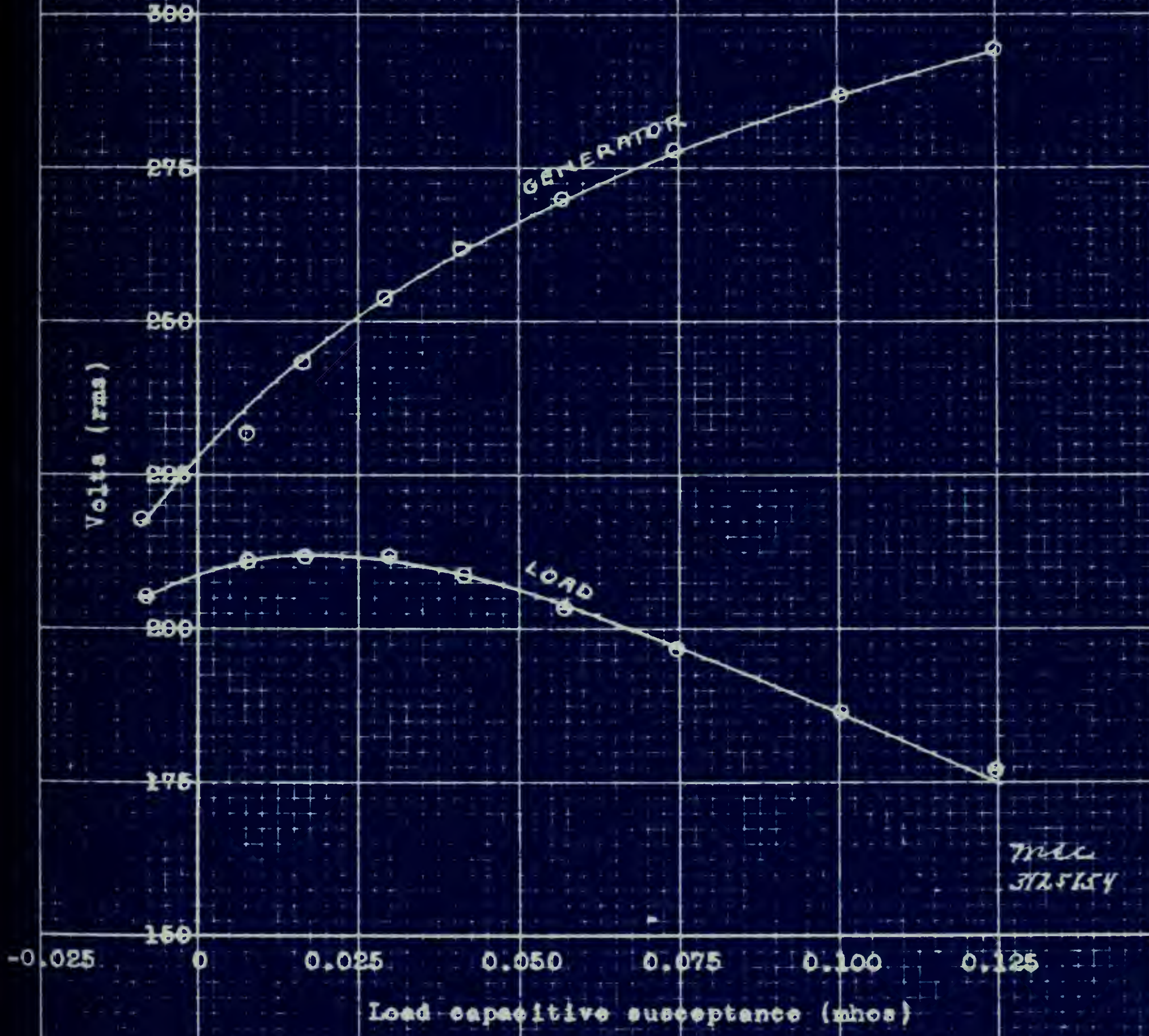


Figure XXVIII
Generator and load voltages
Runs 23-79 to 23-87 inclusive
Load conductance - 0.082 mho



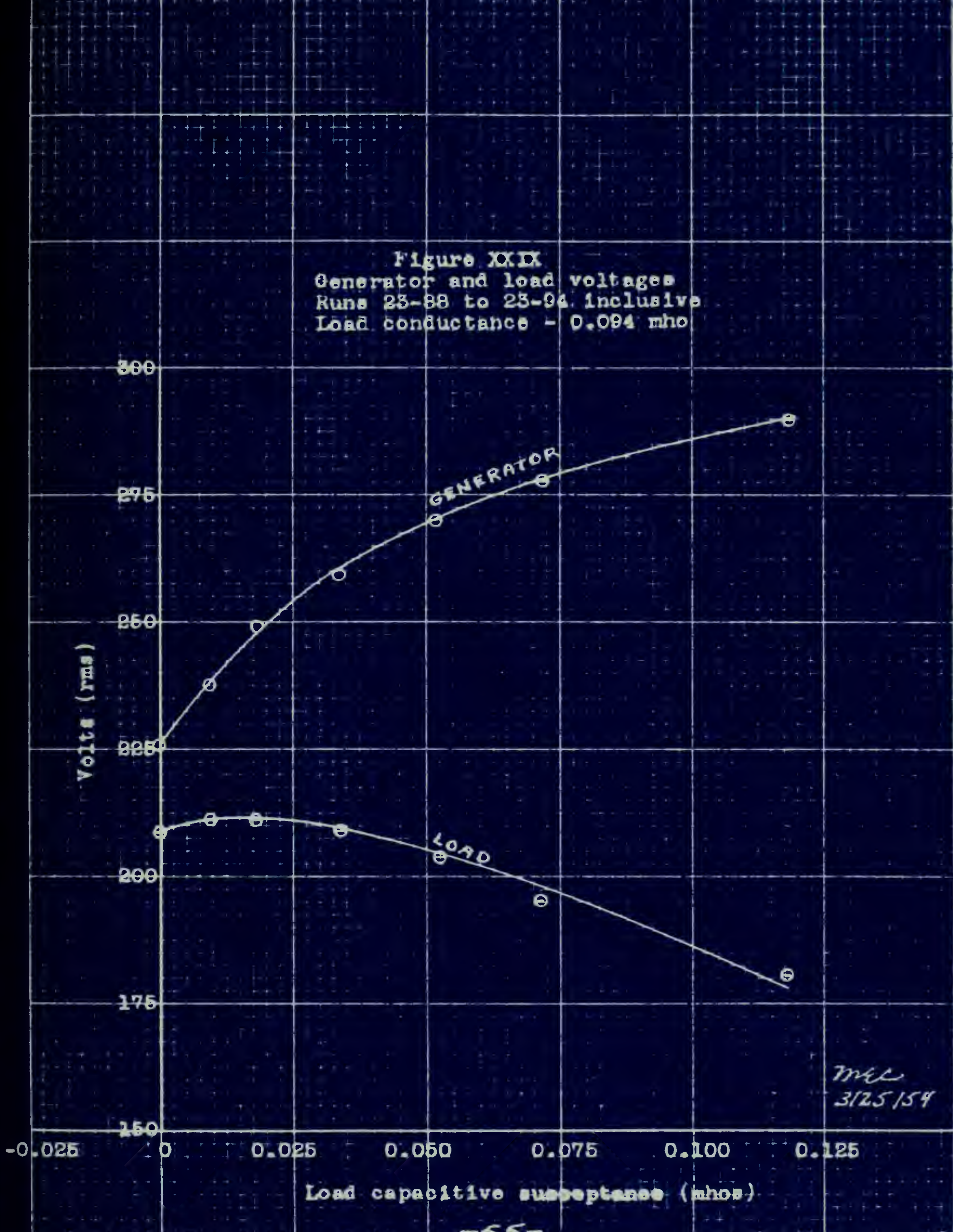


Figure XXIX
Generator and load voltages
Runs 23-88 to 23-94 inclusive
Load conductance - 0.094 mho
300
275
250
225
200
175
150
Volts (rms)
GENERATOR
LOAD
-0.025
0
0.025
0.050
0.075
0.100
0.125
Load capacitive susceptance (mhos)
MEC
3/25/54

Figure XXX

Generator Voltage

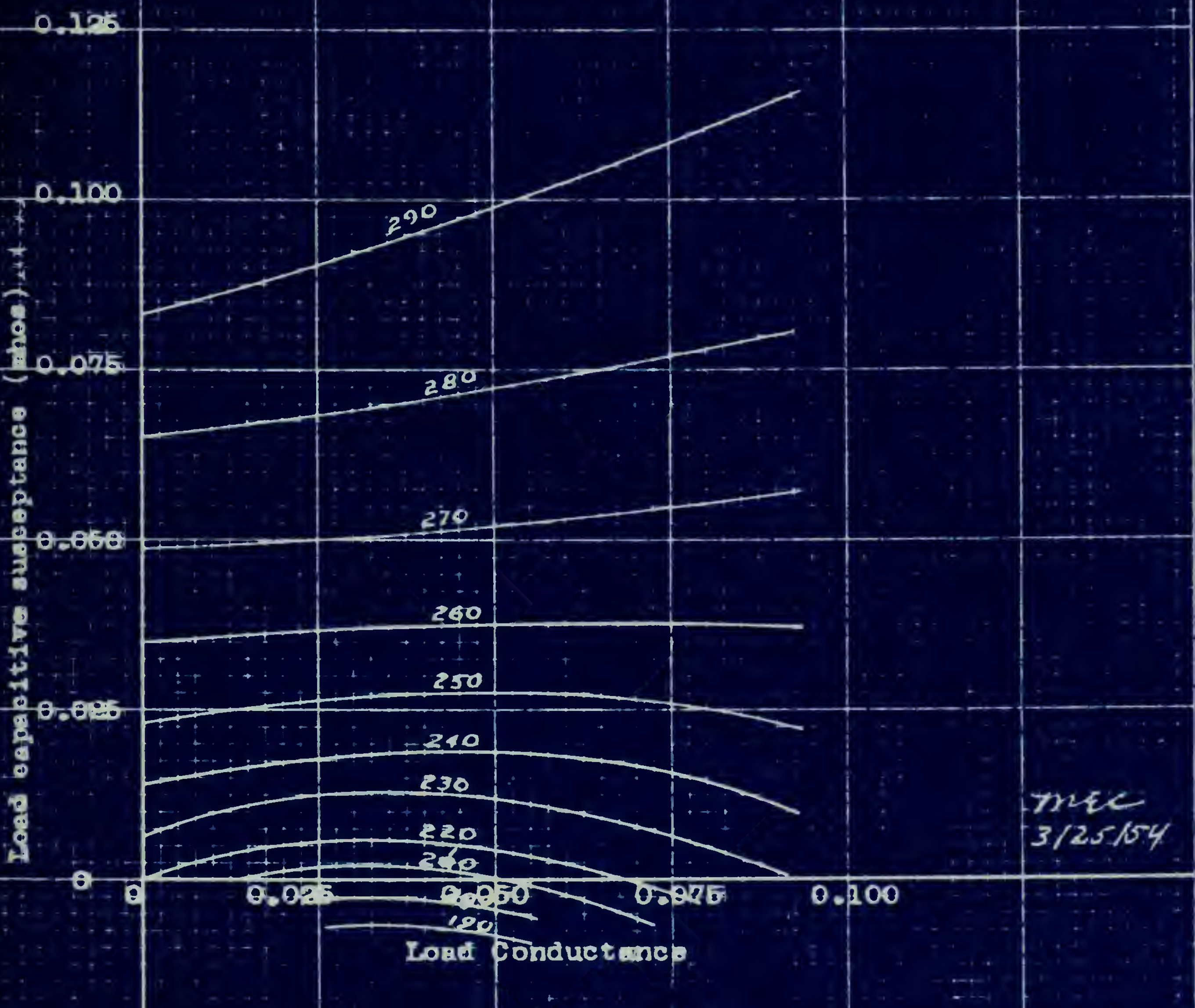
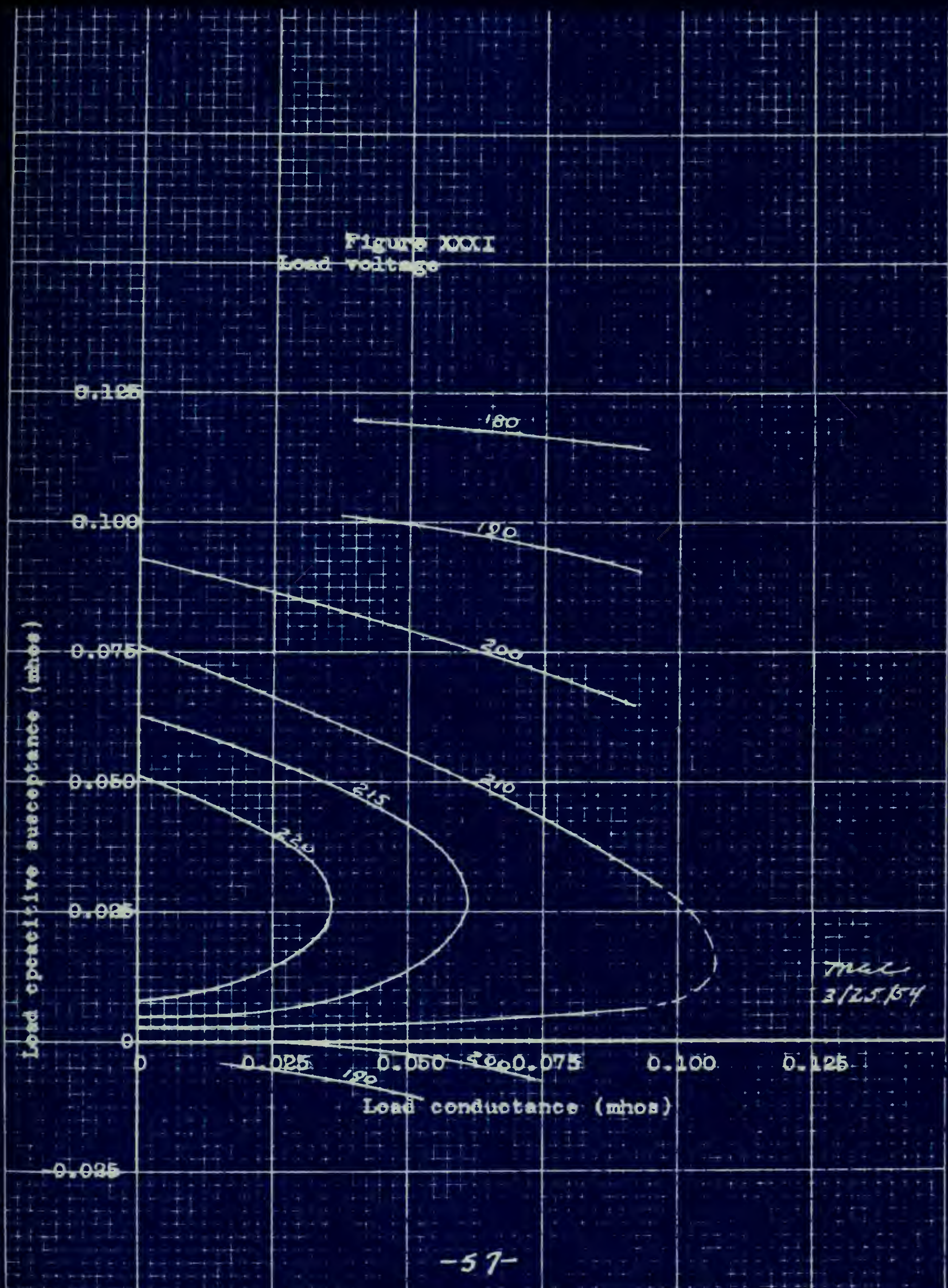


Figure XXXI
Load voltage



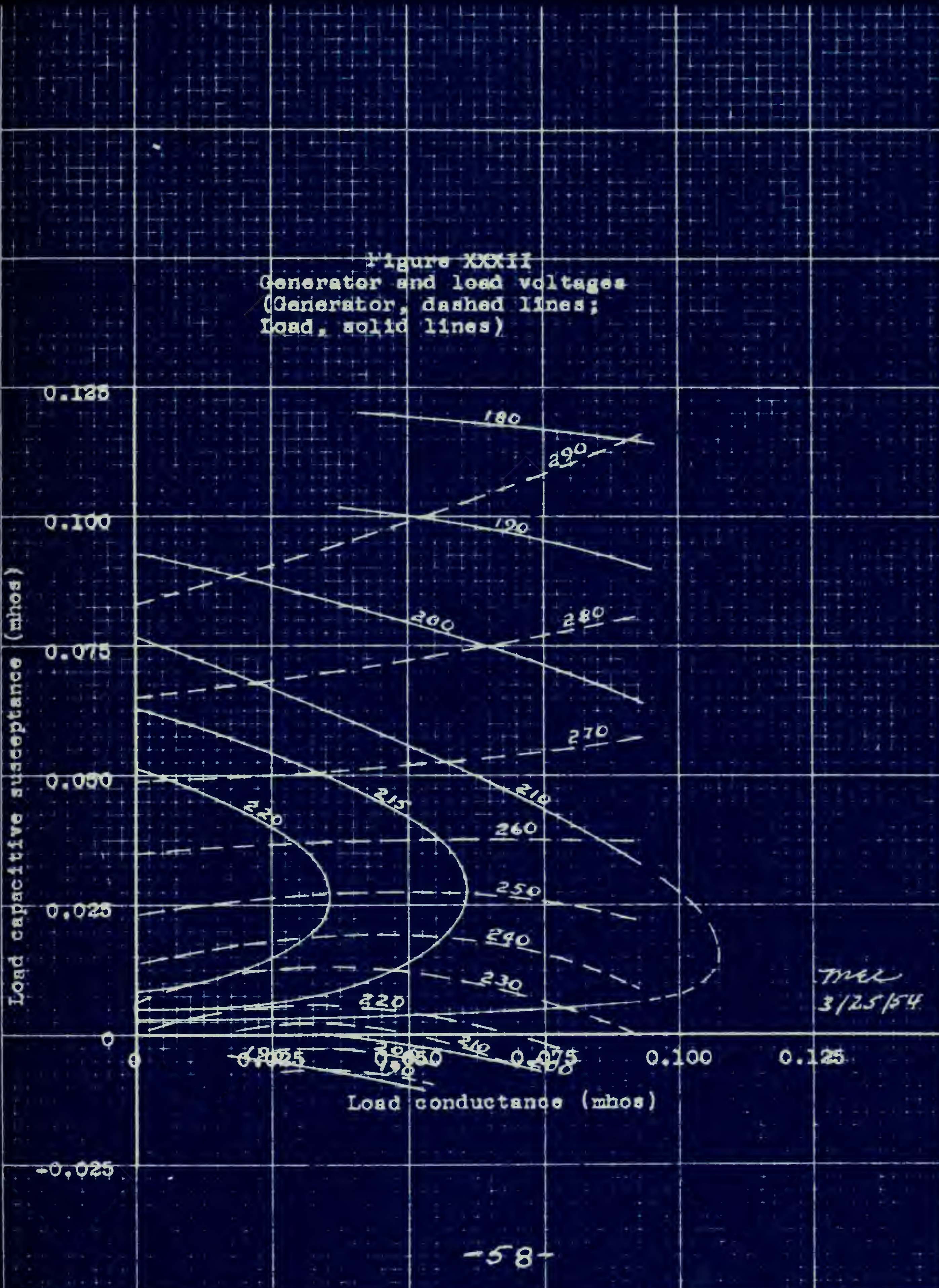


Figure XXXII
Generator and load voltages
(Generator, dashed lines;
Load, solid lines)

range of control with the available reactors, and it produced a reduction of generator voltage of about 15 volts and a reduction of load voltage of about 5 volts. This range of control was entirely inadequate for motor starting tests or tests with a wide range of inductive loads. Since larger reactors of the proper type were not available, the system was not tested with automatic control.

Chapter IV

DISCUSSION OF RESULTS

4.1 Induction Generator Terminal Characteristics

It is evident that the admittance-diagram voltage map of Figure XIX shows how the generator voltage increases as the capacitive susceptance of the connected load increases, and how much the susceptance must be increased to maintain constant generator terminal voltage as the conductance of the load increases. It has previously been stated that the variation of voltage with susceptance along a vertical line of constant conductance is primarily a function of the magnetizing susceptance of the generator, and that the radii of the voltage arcs are primarily a function of the rotor leakage inductance. It is possible to approximate this map with a linear mathematical equation, but the expression is rather lengthy and cumbersome.

The comparison of the experimentally determined voltage maps of Figures XXX and XXXI with the voltage map of Figure XIV, which was obtained by an analysis employing conformal mapping based on the experimentally determined generator characteristic of Figure XIX, shows that the experimentally determined terminal characteristic and the analysis are both substantially correct because the agreement between the maps of Figures XXX and XXXI with the predicted result is excellent. This result indicates that the simple procedure described in Article 2.1 is satisfactory for obtaining the generator characteristic. This experimental approach

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to obtaining the generator characteristic will probably be cheaper and more accurate than a theoretical analysis leading to the same result; therefore it will generally be more practical to determine the generator characteristic experimentally when the generator is available to be tested. The method of portraying the characteristic and the method of obtaining it were originated in a project at the U. S. Naval Boiler and Turbine Laboratory.

The method of using conformal mapping techniques to obtain a circumspect picture of the effect of coupling networks has never, to the knowledge of the authors, been applied to this problem before. It is believed that this method will, after a little practice, be found to be the quickest and easiest way to analyze the problem. Most conformal mapping processes appear formidable and laborious, but because of the extreme simplicity of the admittance-impedance relations involved in this case, it is possible to use several tricks to shorten the process. The authors have had some experience with this technique and with handling the same analysis and similar problems with mathematical equations. This experience indicates that it is faster to map the problem several times to find an optimum than it is to obtain the same solution mathematically.

4.2 Short-Circuit Performance of Series-Capacitor-Coupled Induction Generators

The short-circuit tests proved conclusively that series-capacitor-coupled induction generators can produce sustained

short-circuit currents. The previous discussion of series couplings should make it clear that capacitor coupling is not only equal to inductor coupling in this respect but is, in fact, superior because capacitor coupling can produce a larger short-circuit current for a given total capacitance. This result should indicate that further work with capacitor coupling is justified.

The short-circuit tests reported in the previous chapter are general cases of low impedance faults, despite the fact thay they were all initiated from unity power factor load conditons. Regardless of the type of load, the operating conditon of the generator corresponds to some condition represented by some point on the terminal characteristic above the minimum voltage arc, if the generator is excited. When a short circuit occurs, the transient path in the phase or phases shorted may be approximated by a line from the initial operating point to a point on the susceptance axis determined only by the sum of the susceptances of the shunt capacitor and the series capacitor. These two capacitors are actually in parallel after the short occurs. The type of load can have no effect upon the transient phenomenon because the load is bypassed by the short. If the short circuit is slightly inductive, the impedance of the path through the series capacitor and the short is reduced. In order to avoid excessive voltage drops across the series capacitor in normal operation, the susceptance of the series capacitors will have to be large enough to produce more than adequate

short-circuit currents in most cases. The susceptance of the series capacitors is roughly proportional to the generator rotor leakage susceptance.

Series capacitor coupling has two advantages over inductor coupling: the former produces larger short-circuit currents for a given amount of capacitance and can be used to produce a tendency toward constant voltage operation. However, it is possible to cause voltage collapse with capacitor coupling by applying excessive inductive loads; whereas this result can be avoided with inductor coupling, but not without incurring other disadvantages. With the capacitor coupling it is necessary to provide some margin of capacitance to present this voltage collapse.

4.3 Unbalanced Load

Series capacitor coupling can be used to make the load voltage less sensitive to the admittance of the load, and it seems entirely reasonable under these circumstances that small unbalance of the phase loads should not greatly affect the load voltage. The experimental results obtained from a single test such as was conducted for this thesis are not adequate support for a sweeping general statement, but the results obtained do indicate, at least, that unbalance up to 50 per cent of full load is relatively unimportant insofar as it affects the voltage. It seems probable that the smaller degrees of unbalanced load likely to be encountered in practice will have only a negligible effect.

4.4 Test Without Frequency Control

When the speed of the prime mover is allowed to decrease with load, the frequency of the induction generator output is decreased by an amount proportional to the sum of the speed droop plus the increase of slip with load. The susceptance of the capacitors decreases by an amount proportional to the decrease in frequency. This decrease in both the shunt and series capacitive susceptance lowers the open-circuit voltage and decreases the rate of increase of voltage with load. It is possible that operation without frequency control would be satisfactory in some application. In this case the series capacitance might be adjusted to cause a controlled increase of voltage to offset the effect of the decrease of frequency. Such a system could probably be adjusted so that the torque-speed characteristic of an induction motor supplied from such a system would not be appreciably different than the characteristic of the same motor supplied from a source of constant frequency and constant voltage. It should be noted that the voltage did increase as the frequency decreased as the load increased in the test run reported in this thesis.

4.5 Voltage Regulation for Unity Power Factor Loads

The least voltage variation over the load range obtained with the gamma coupling network amounted to 8.3 per cent, and this result was obtained with only half as much series capacitance as the calculated optimum amount. When the predicted optimum amount of series capacitance was tried,

the voltage collapsed when the first one-third of the load was switched on. It was still hoped at the time of these tests to test the system with automatic control over a wide range of inductive loads, and it was decided not to sidetrack the main line of investigation further to clear up this point. The test of unity power factor loads with the gamma network coupling was undertaken as a side issue after it was discovered during the survey of the literature that Peake (25) had searched unsuccessfully for a means of regulating, within 10 per cent, the voltage across a unity power factor load supplied from an induction generator. Presumably, this result could be used in some application. The use of the gamma network to obtain this desired result was conceived, and an analysis indicated that excellent results could be achieved. The results obtained the the laboratory were disappointing and are counted a failure even though a variation of only 8.3 per cent was achieved because this is not considered to be satisfactory for most purposes.

It is believed that the failure was due to poor laboratory technique, and that the results neither prove nor disprove the value of the gamma network in this application. It was realized before the tests that the resistors wound on ceramic cores in the resistor banks were slightly inductive: the mistake was made in thinking that the inductance of the resistors could be ignored after it was found to be slight. Consider the case where 15 ohms of series capacitance is used to couple a nominal resistor with a lagging power factor of

0.99. When the resistor has a conductance of 0.0111 mho, the one-third load, per phase, the nominal resistor is roughly equivalent to a 100 ohm resistor in series with a 13-ohm inductor. The effective series capacitive reactance is then reduced from 15 to 2 ohms. This explains why the load voltage dropped more than was expected at small values of load conductance. This result does show that compensated loads should be slightly overcompensated to avoid this condition. It should be noted that the pi network reduces to a gamma network when the load shunt capacitance of the pi network is zero. This is the case along the horizontal axis of Figure XXXII, and the load voltage is very nearly constant along this axis. Examination of this figure will reveal that the voltage variation is only about 1 % in this case.

By adding another capacitor to the gamma network to form a pi network to couple a unity power factor load, a variety of load-voltage characteristics can be obtained. Any horizontal line on Figure XXXII represents a variable resistive load in parallel with a fixed inductor (below axis) or fixed capacitor (above axis). With an inductor, a rising characteristic is obtained; with a capacitor the voltage droops. The flat voltage region is not necessarily found on the horizontal axis: a different set of parameters could be used to lower or raise this region. In general, the capacitance distribution can be adjusted to move the whole map vertically, to rotate the whole map, or to raise the voltage level without causing appreciable change in the contours. The rotation

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is limited to about 90° in either direction, and the voltage limits are due to saturation and the minimum magnetizing susceptance. Increased series capacitance tends to lower the map, rotate the contours clockwise, and raise the voltage level. Decreased generator shunt capacitance tends to raise the contours vertically and to lower the voltage level. In a pi network, the load shunt capacitance can be adjusted to raise and lower the map with relation to the actual load admittance. By judicious selection of parameters, the shape and orientation of the contours can be changed within certain limits as desired. It is important to realize that the designer of the coupling network has this flexibility to use to his advantage.

4.6 Fixed-Element Regulation

The limits of shaping the voltage map and the effects of approaching the limits have not been completely explored. The capacitance in the pi network tested was adjusted to obtain the largest possible area of very small voltage gradient, and Figure XXXII is a picture of the result. This figure also shows that the pi coupling network could be used to obtain nearly constant load voltage for an inductive load of about 0.9 to 0.7 power factor. It is probable that the slope of the constant voltage lines on the upper part of the diagram could be changed to maintain nearly constant load voltage for any narrow range of lagging power factors by adjusting the circuit parameters. The map also shows that the pi network can not be used to maintain constant load voltage

over a wide range of inductive loads. It has been previously explained that at exact match of the generator characteristic and the voltage map obtained by assuming a constant load voltage and referring the load admittance back through a shunt capacitor, a series capacitor, and another shunt capacitor is not possible.

4.7 Load Specification

In a system where fault protection is to be obtained by selective switching, a series element must be used in the coupling network for an induction generator. With a fixed series capacitor, the maximum generator voltage required to produce a constant voltage at the load occurs when the maximum power is being delivered to a unity power factor load. For a constant load voltage, the maximum generator voltage can be reduced by increasing the series capacitance. Whether specified or not, there is a maximum voltage above which it is not prudent to operate a given generator, and how much series capacitance is required to stay below this maximum voltage is determined by the maximum power to be delivered at power factors near unity. This point on the load requirement, the maximum real power at a power factor of 0.9 to 1.0, and the maximum allowable generator voltage determine the size of the largest capacitor bank in the coupling network; therefore it is important not to make the specified load larger than is necessary. The minimum capacitance across the generator terminals is fixed by the open-circuit voltage. The size of the variable shunt capacitance,

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regardless of its location, and the size of the capacitor across the load depend upon the specified condition of maximum reactive power occuring at the condition of maximum real power. It is important to limit the load specification to those loads that will actually be encountered. A careless specification of the design load may considerably increase the size, weight, and cost of the coupling network and voltage regulator for an induction generator: the load specification is more important in this case than it is for synchronous generators.

4.8 Adapting the Pi Network to Automatic Control

In considering adapting the pi network to automatic voltage control by changing the effective capacitance in one branch by means of a d-c controlled saturable reactor in parallel with the capacitor bank, the question of which capacitance to control arises. The series capacitor is much larger than either of the other two, and the full load current flows through it; control in this branch is the least effective in terms of range of control in volts per pound of reactor. Control of the capacitance shunted across the generator terminals was proved to be ineffective in the laboratory, and this result is not surprising in retrospect. The coupling network is supposed to cause an increase in generator voltage sufficient to offset the increase in voltage drop across the series capacitor as the load increases, and this balancing process also works in reverse so that the load voltage is insensitive to changes in the generator voltage. Figure XXXII illustrates this point. This diagram can

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also be used to determine what amount of capacitance must be varied to maintain the load voltage constant. Either the upper or lower 200-volt line could be swept across the load area if a capacitive susceptance could be controlled over a range about equal to the maximum inductive susceptance of the load, if the capacitor so controlled were connected across the load. An additional and equal amount of fixed capacitance must also be connected across the load to use the upper line, and the generator operates at a voltage much higher than the load voltage in this case. To use the lower 200-volt line almost amounts to using the gamma network and variable compensation to make the load always appear to be a unity power factor load. However, since the job can be done using the 5 ohms of series capacitance, which is not the best value for a gamma network, it is apparent that the size of the series capacitive reactance is not so critical as the mention of the gamma network might imply. Possibly, the series capacitor can be smaller than is needed for a gamma network by arranging to make the load appear inductive at all times. It is possible that the generator could operate at a voltage lower than the load voltage in this case. Specifically, the generator shunt capacitance and series capacitance should be adjusted until the desired load voltage line almost coincides with the 0.8 lagging power factor locus on the load terminal admittance diagram. The 130-volt load voltage line on Figure XVI is about in the right position. Notice that the generator operates at about 120 volts in this case. Then the shunt capacitor across the load must correspond

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to the vertical distance from the voltage line to the farthest low point on the load range, which will be the point of maximum load susceptance. This permits shifting the load area up and down so that the load voltage line can pass through any point in the load area. It is expected that the optimum will be found to be flat as it has been found to be in all other cases. This approach will probably lead to the coupling network of least cost and weight, and it is suggested that the next experimental work should follow this approach through to determining the solution of least weight.

It was not expected by the authors that fixed element regulation would be satisfactory without any variable range of susceptance, but it was hoped to produce coarse regulation with fixed elements so that the variable susceptance needed to produce find regulation would be appreciably reduced. The discussion above leads to the conclusion that the variable susceptance needed is not appreciably reduced. The coarse regulation concept should be abandoned.

4.9 Use of Transformers

It may appear very inviting to use transformers to increase the apparent admittance of the capacitors of systems operating at voltage levels below the voltage at which the size of capacitors becomes proportional to the KVA rating instead of the capacitance. This idea should be used cautiously: when a short circuit occurs, the voltage across the generator shunt capacitor and the series capacitor becomes very large which would increase the susceptance of

transformers in these branches so that the combination of transformer magnetizing susceptance in parallel with the capacitor connected to the secondary could form a blocking impedance. This result might be desirable in the generator shunt branch, depending on the various parameters, but it should be avoided in the series branch. Transformers can be used across the load branch, and the transformers function might be combined with the saturable reactor function on one three-legged core in this branch.

4.10 Regulator Element Characteristic

The element referred to here is the entire feedback loop. This element monitors the load voltage and delivers a direct current of the proper magnitude and direction to correct the load voltage error. The field current of a synchronous generator must be increased to raise the load voltage. With a saturable reactor in parallel with a capacitor in an induction generator coupling network, the direct current controlling the susceptance of the branch must decrease to increase the effective capacitance of the branch and raise the load voltage. The characteristics required for the two types of generators are just opposite. This fact will cause no difficulty when it is recognized: it is quite as easy to obtain one characteristic as the other. The characteristics would be the same if the saturable reactor were in series with the capacitor being controlled, but the direct current would have to be a maximum in order to achieve the largest effective capacitance.

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4.11 Effect of Frequency and Voltage Upon Size

The size and weight of the coupling network for an induction generator are of the same order of magnitude as the size and weight of the generator itself, which would be intolerable except that a high-speed induction generator can be less than half as large as an equivalent synchronous generator. The size of the capacitors is important in terms of KVAR, not in terms of farads. For a single capacitor, the reactive power is equal to $2 \times 3.14 \times fCV^2$. It is apparent that the physical size of capacitors is smaller in systems operating at high frequency and high voltage. Fortunately, the induction generator itself is also best-suited to these same systems.

4.12 Harmonic Currents

No progress was made on the problem of reducing the harmonic currents arising from the use of saturable reactors except for discovering in the literature the means of avoiding difficulty with harmonics that are multiples of 2 or 3. Bear-in mind that the fifth is the lowest harmonic that need be encountered and that the susceptance of capacitors increases with frequency while the susceptance of inductors decreases with frequency, it is possible to evaluate the effect of the pi network in reducing difficulty with harmonic currents. The circuit diagram of an induction generator system consists of the familiar equivalent circuit of the induction machine connected to a coupling network and load. The voltage level of steady state operation is determined by the non-linear magnetizing susceptance of the generator and the susceptance

of the capacitors in the coupling network, and the impetus to operate is furnished by the negative resistance of the rotor. There is neither a voltage source nor a current source in the circuit. The magnitude of the admittance of the coupling network and the generator viewed from the load must equal the magnitude of the load admittance at the fundamental frequency since the current and voltage magnitudes are identical in both directions from the load terminals. At the frequency of the fifth harmonic, the capacitive susceptance of the admittance looking toward the coupling network is five times greater than its value at the fundamental frequency, and the magnitude of the load susceptance is only 1/5 as large as its fundamental value. Considering the reactor across the load terminals to be a source of harmonic currents, it can be seen that 90 to 95 per cent of the harmonic current will circulate harmlessly in the pi network. Whether the pi network is sufficient protection for the load and generator depends upon the strength of the harmonic currents produced by the reator. This point should be investigated.

If the pi network is not sufficient protection for the load or generator, an additional small winding could be wound on the core and connected to an inductor-capacitor series tuned to the most troublesome harmonic frequency. If these measures are not sufficient, a whole new area will have to be investigated. Aside from the avoiding harmonic currents of frequencies that are multiples of two or three time the fundamental, the published literature sheds very little light on this problem.

Chapter V

CONCLUSIONS

1. The generator characteristic can be determined with sufficient accuracy for design purposes by the procedure described in Article 2.1.

2. The method of analysis by mapping admittance and impedance loci to predict the effects of coupling network has been verified.

3. With properly adjusted coupling network parameters, series-capacitor-coupled induction generators will produce sustained short-sircuit currents large enough to actuate selective switching for either polyphase or single phase low impedance faults.

4. Moderate unbalance of load among phases does not have a serious effect upon load voltage if the load is coupled to an induction generator through a series capacitor.

5. The gamma network for coupling unity power factor loads appears promising, and the laboratory results neither prove nor disprove the value of this coupling network.

6. The pi network can be adjusted to maintain very nearly constant load voltage over a narrow sector of inductive power factors and a wide variation of real power, but fixed capacitors in a simple configuration can not produce a nearly constant load voltage over a wide sector of power factors and a large range of real power.

7. When the pi network parameters are adjusted to the optimum values for producing coarse voltage regulation, the magnitude

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[illegible]

[illegible]

[illegible]

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of controllable susceptance needed to maintain exactly constant load voltage is not appreciably reduced from the magnitude required without any coupling network other than a single shunt capacitance and parallel reactor.

8. Load specification, because of its effect upon the size of the coupling network elements, is more important for induction generators than for synchronous generators.

9. The coupling network size will be of the same order of magnitude as the size of the induction generator unless some entirely new idea is developed; therefore the only meaningful way to compare induction generators and synchronous generators is to include all the excitation and regulating equipment as entirely changeable to the generator weight, size, and cost.

CHAPTER VI

RECOMMENDATIONS

Approach to Design Problem

1. The generator characteristic should be determined experimentally as the first step in designing a coupling network and voltage regulator.

2. The mapping analysis should be used to predict the effects of proposed solutions to avoid wasted effort.

3. The load specification should be limited to those loads that will actually be encountered, and the margin of system stability and the requirement for starting motors should be specified in some specific manner. Otherwise, the designer will be required to use unnecessarily large capacitors.

Short-Circuit Performance

4. That the magniture of short-circuit currents produced by induction generators with series capacitor coupling can be predicted should be verified experimentally. It should also be proved that the type of load affects only the sub-transient current.

5. The load and reactive power division and short-circuit performance of paralleled induction generators should be investigated.

Fixed-Element Regulation

6. In an application where frequency droop with load can be and is tolerated to avoid the added weight or expense of a frequency control, the coupling network should be adjusted to cause a compensating rise in voltage with increased load.

7. The efficacy of the gamma network coupling for unity power factor load voltage regulation should be investigated with more attention being given to the precise load power factor.

8. If the gamma network is to be used with a compensated load, the load should be slightly overcompensated rather than undercompensated.

Automatic Voltage Control With Pi Network Coupling

9. The concept of coarse voltage regulation by means of fixed capacitors should be abandoned.

10. The practicability of using a buck-boost voltage regulator with the bridge rectifiers reversed for controlling a saturable reactor should be investigated.

11. In adapting the pi network to automatic control, the saturable reactor should be used in parallel with the load shunt capacitance.

12. The predicted worth of the pi network for protecting the load and generator from harmonic currents should be verified experimentally.

13. The automatic voltage regulator and coupling network of fixed capacitors in a pi configuration with a d-c controlled saturable reactor will probably have a minimum weight and cost near the following adjustment of parameters:

Generator shunt capacitance: equivalent to the terminal susceptance of the generator operating at rated voltage and rated real power.

Series capacitance: of susceptance equal to the radius of the rated voltage arc on the generator characteristic

plus 50 per cent.

Load shunt capacitance: susceptance equal to 60 per cent of the maximum load susceptance.

Load shunt d-c controlled saturable reactor: range of control of susceptance equal to maximum load susceptance.

The optimum is expected to be flat. This mode of operation includes an exactly resonant load shunt branch and the current should be investigated. If the resistance of the reactor is too small to impose a reasonable limit, the resistance should be increased, or the load shunt capacitance can be increased and the other capacitances adjusted as necessary.

14. The system of minimum weight should be determined and compared with the equivalent synchronous generator and exciter at appropriate frequencies.

15. If the comparison favors the induction generator, the problem should be assigned to a development facility. There is no problem blocking the creation of a successful design, except possibly the problem of harmonic currents.

Use of Transformer Action to Increase Effective Capacitance

16. The use of transformers to increase the operating voltage level of capacitors in order to save weight and cost should be considered only with due regard for the possibility of resonance between the transformer magnetizing susceptance and the capacitors at high voltages, particularly at the voltages to be encountered under short-circuit conditions.

APPENDIX

APPENDIX A

SUPPLEMENTARY INTRODUCTION

A-1 Minimum Magnetizing Susceptance

The relation between the generator terminal voltage and the value of the capacitive reactance X_c in Figure XXXIII is shown by the diagram of Figure XXXIV. The generator voltage is determined by the intersection of the generator magnetization curve and the straight line with a slope equal to X_c. This is a diagram in the frequency domain: the straight line would have to represent an integral relation in the time domain, which is not possible. The diagram is not entirely valid because it implies that both the voltage and the magnetizing current are sinusoidal, but it illustrates the existence of a minimum magnetizing susceptance. Notice that if X_c were greater than X_c', the voltage would collapse. B_m', the reciprocal of X_c', is called the minimum magnetizing susceptance. Notice that it is not possible to maintain a steady voltage less than V_{min} because operation of the generator is not stable at any smaller voltage. This explains the dashed line of minimum voltage on Figure XIX.

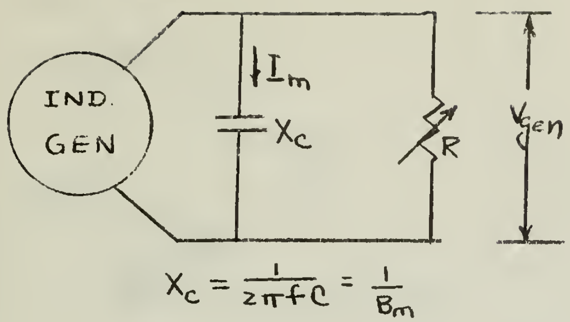


Figure XXXIII. Circuit diagram.

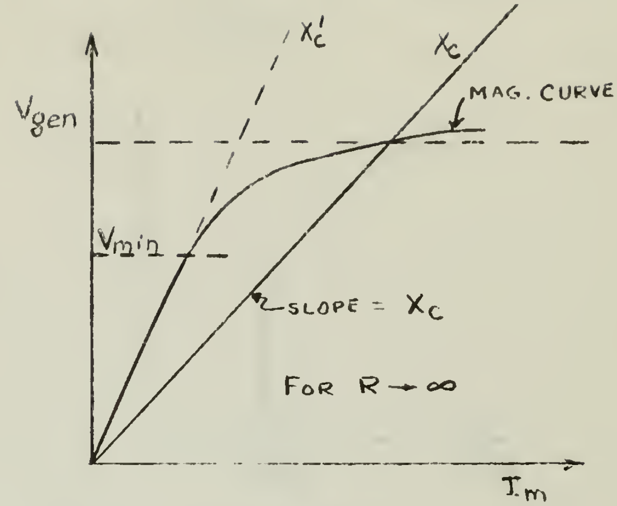


Figure XXXIV. Relation of capacitance and voltage.

Figure XXXIV shows that the generator voltage would change if the value of X_c were changed, but it does not indicate what effect the magnitude R has upon the generator voltage. Several methods of analysis (14, 15, 18, and 24) have been developed to predict the conditions of operation, including generator voltage, for an induction generator connected to any generalized load. Of these, the Friauf method (24) is the simplest.

A-2 Friauf Method

Starting with the equivalent circuit of an induction machine as shown in Figure XXXV, the following relations are derived:

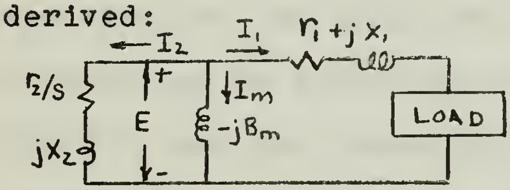


Figure XXXV. Equivalent circuit of induction machine.

$$I_1 + I_2 + I_m = 0 \qquad (2)$$

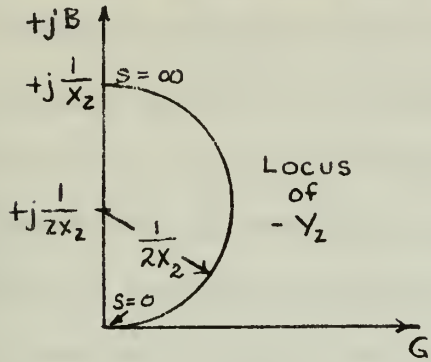
$$E(Y_1 + Y_2 - jB_m) = 0 \qquad (3)$$

$$Y_1 = - Y_2 + jB_m \qquad (4)$$

$$Y_2 = 1/(r_2/s + jx_2) \qquad (5)$$

Notice that the slip is negative. It can be shown that the locus of Y_2 on an admittance diagram is a semicircle of radius

equal to $1/_2X_2$ as shown on Figure XXXVI. B_m is a function of the air gap voltage E as shown in Figure XXXVII.



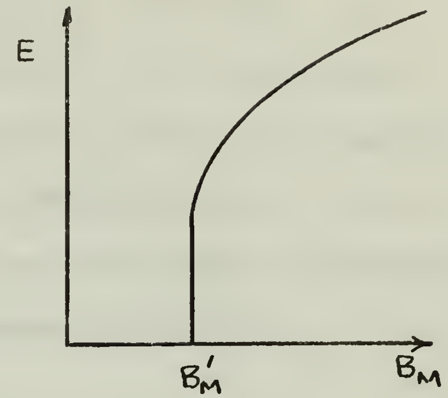
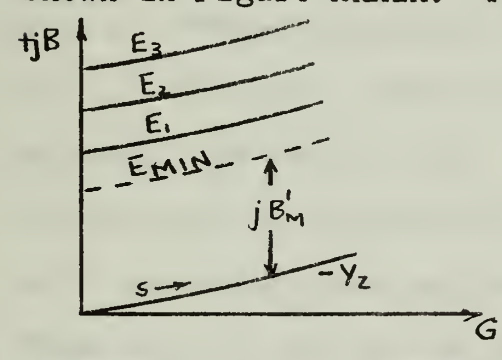


Figure XXXVI. Locus of Y_2.   Figure XXXVII. B_m-E plot.

If all the circuit parameters are known, the air gap voltage map on an admittance diagram can be constructed as shown in Figure XXXVIII. The relation of the admittance vectors is shown in Figure XXXIX. For any arbitrary load,



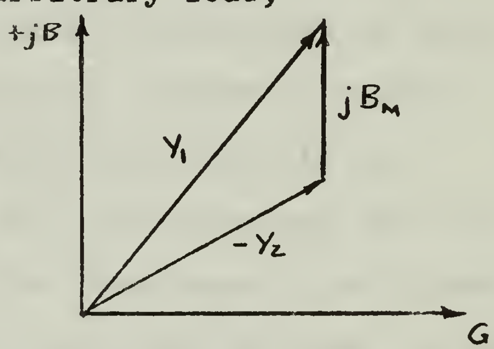
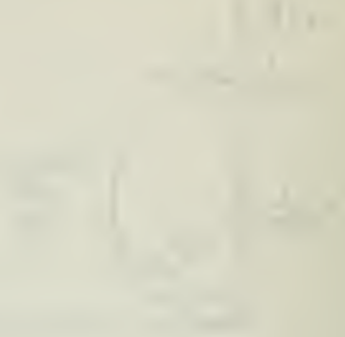


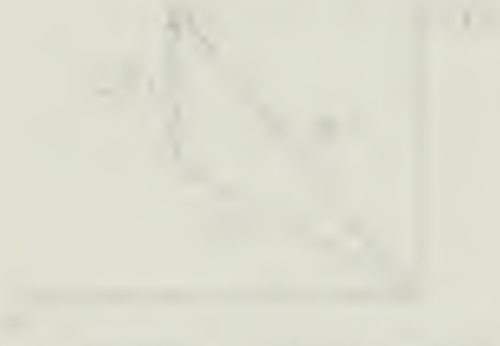
Figure XXXVIII. Air gap voltage map.

Figure XXXIX. Relation of admittance vectors.

the value of the admittance Y_1 can be computed, the air gap voltage can be determined from the voltage map of Figure XXXVIII, and the generator voltage and load voltage can be calculated by linear circuit analysis.

Simplicity is the virtue of this method, but the method gives a picture of conditions at the air gap instead of conditions at the generator terminals. This latter picture could

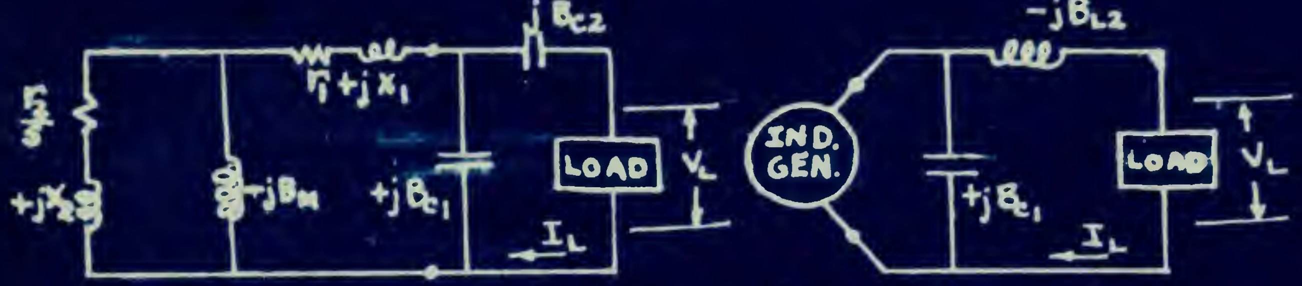




be obtained by conformal mapping and shifting to account for r_1 and x_1 in a manner analogous to the analysis used herein to determinethe effect of coupling networks. The authors prefer to determine the generator terminal characteristic directly instead of the circuit parameters when the generator is available to be tested, but knowledge of the Friauf method is required to understand the effect of machine characteristics upon the terminal characteristics.

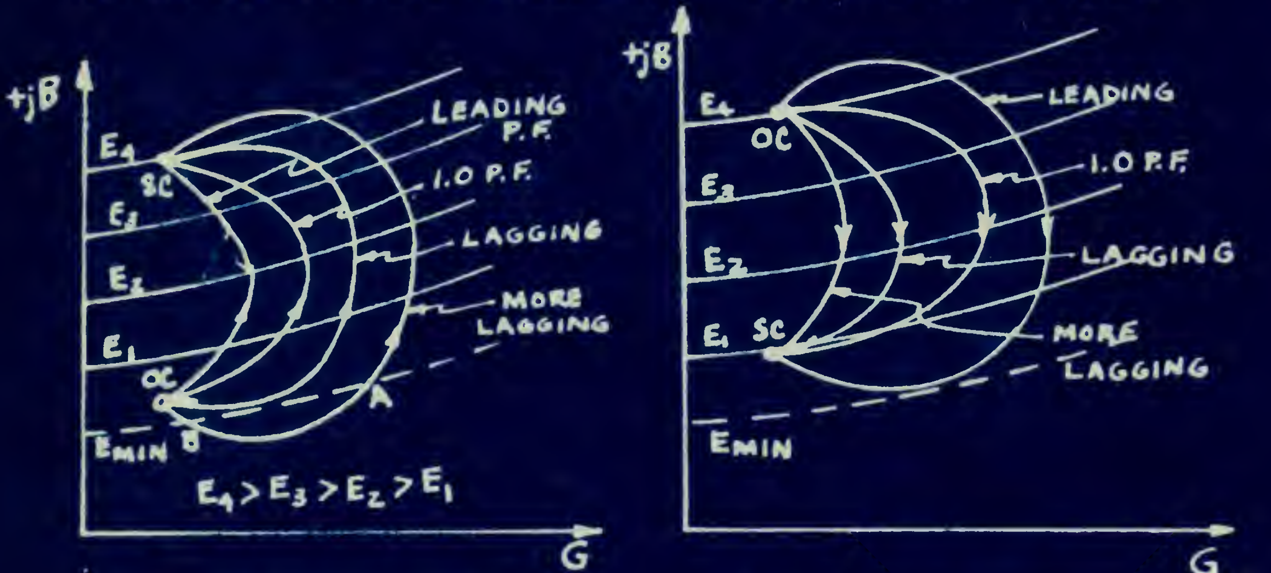
A-3 Series Coupling

If only shunt capacitance is used to couple the load to the generator as shown in Figure XXXIII, a short circuit across the load terminals also shorts the capacitor, and the generator voltage collapses. A series element is used to limit the short-circuit current to prevent this voltage collapse. Series capacitor coupling was investigated by Swift (21), and series inductor coupling was studied by Goode, Hoffman, and Searle (20). The basic test circuits are illustrated in Figure XL(a) and (d). The approach used in both investigations was to plot the admittance Y_1 as viewed from the air gap on the air gap voltage map as shown in parts (b) and (e) of Figure XL. The qualitative variation of load voltage with load current is shown in parts (c) and (f). Notice that either method of coupling imposes a power limit upon the generator and coupling network. Notice also that the open-circuit point is above the short-circuit point with inductor coupling and below with capacitor coupling. The two points are marked SC and OC on the diagrams. Most loads are



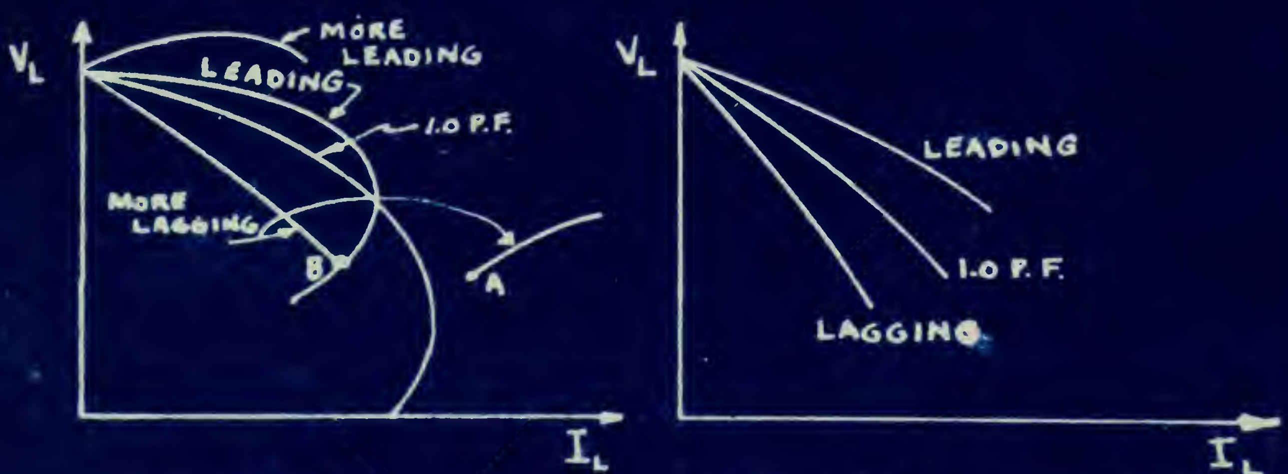
(a) Series capacitor coupling.

(d) Inductor coupling



(b) Load admittance loci with capacitor coupling.

(e) Load admittance loci with inductor coupling.



(c) Effect of capacitor coupling upon load voltage variation.

(f) Effect of inductor coupling upon load voltage variation.

Figure XL. Comparison of the effects of series capacitor and series inductor coupling.

inductive loads in any power system, and the coupling used with the generator should be suited to this type of load. Realizing that the generator voltage will collapse whenever the Y_1 admittance locus crosses the arc of minimum voltage because the imaginary part of Y_1 has become less than the minimum magnetizing susceptance, it can be seen from Figure XL that inductive loads will not cause voltage collapse with properly adjusted inductor coupling. On the other hand, the voltage would collapse at point B with capacitor coupling.

Series capacitor coupling tends to maintain the load voltage constant because the excitation of the generator is increased as the current through the series capacitor is increased; this is the principal advantage of series capacitor coupling. Actually, the effect of the capacitor coupling is somewhat more complicated than this statement suggests, but the tendency to improve the voltage variation can be obtained. However, it has been believed by some that highly inductive low impedance faults would result in voltage collapse, i.e., that the transient path would cross the minimum voltage arc. The authors do not agree with this opinion. The reactance of the fault is of no importance if it is much smaller than the reactance of the series capacitor.

Inductor coupling prevents voltage collapse due to low power factor inductive loads when the circuit parameters are properly chosen, but it has many disadvantages. First, the reactor must pass the full load current and must be a low impedance. The generator should be operated just above the

minimum voltage arc, not far up in the saturation region. The load voltage is equal to the generator voltage at open circuit, and this point should be below the saturation region. The short-circuit point must be below the open-circuit point and above the minimum voltage arc: this imposes a severe power limit on the system. The reactor decreases the excitation of the generator as the current through it increases, and tends to cause the voltage level to drop as the load increases. Inductor coupling is not entirely satisfactory.

A-4 Saturable Reactor Control of Voltage

Sharp and Walters (22) used inductor coupling with a d-c controlled saturable reactor in parallel with the shunt capacitor and, with manual control of the direct current, were able to control the load voltage by varying the effective susceptance of the parallel combination of the shunt capacitor and the saturable reactor. The system was not entirely satisfactory because of low efficiency and difficulty with harmonic currents. The authors believe that the efficiency would not necessarily be too low in a system designed from the beginning to operate in this manner, but that the difficulty with harmonic currents is a valid objection. Furthermore, a relatively large saturable reactor and a series inductor add very considerably to the weight and size of the system.

A-5 Other Methods of Voltage Control

Synchronous condensors immediately come to mind as the commonest means of variable capacitance. The KVA rating of the synchronous condenser to supply reactive power in this

system would be nearly the same as the KVA rating of the induction generator.

Another method that has been tested uses a saturable inductor with a sharply breaking magnetization curve in parallel with the load. This acts as a bypass valve that prevents the load voltage from exceeding the saturation voltage. This chopper action makes the load voltage have the appearance of a square wave.

Appendix B

DETAILS OF PROCEDURE

B-1 Initial Excitation of the Generator

Statements have been published about exciting the induction generator that are contrary to the experience of the present writers. It was never necessary to connect the generator to another voltage source, to flash the generator to magnetize the rotor, nor to charge the capacitors in order to excite the generator initially. It was found, however, that it was generally necessary to connect a greater amount of capacitance to the generator to excite it initially than was required to operate it in the normal voltage range. After some experience, the authors adopted the practice of connecting a small amount of excess capacitance through a separate switch in one phase directly across the generator terminals. When the generator rotor had been brought up to speed, this extra capacitance was switched on to initiate the voltage rise and switched off when the voltage began to rise. Other circuit elements had previously been adjusted to determine the steady operating condition reached at the end of the voltage rise. This practice was successful when one precaution was observed: the generator had to be disconnected suddenly when it was turned off so that the voltage would not decay slowly and demagnetize the rotor. When the extra capacitance is not sufficient, the generator can usually be excited by increasing its speed. In extreme cases, an extra bank of capacitors was connected to all three phases in delta. Another voltage source

was never used to excit the induction generator; therefore, it would not be necessary to have another voltage source available aboard ships ncr in aircraft.

APPENDIX C

C-1 NONE.

C-2 Summary of Data and Calculations for Induction Generator Terminal Characteristic

Run No.	Freq. cps	V_{gen} (Volts)	I_{line} (amp)	KVA	KVAR	$\frac{VARS}{V^2}$	KW	Angle (deg.)	$\frac{WATTS}{V^2}$
1-1	59.91	117.3	6.70	1.36	1.312	0.0953	0.352	75-00	0.0256
1-2	60.02	141.0	8.70	2.13	2.056	0.1032	0.550	74-40	0.0276
1-3	60.05	160.2	10.00	2.78	2.736	0.1062	0.532	79-00	0.0207
1-4	59.99	179.3	11.05	3.44	3.43	0.1081	0. --	---	---
1-5	59.98	201.3	13.32	4.65	4.62	0.1140	0.484	84-00	0.0120
1-6	59.84	220.0	15.47	5.90	5.34	0.1101	2.58	65-00	0.0805
1-7	59.74	242.3	18.52	7.79	7.75	0.1320	0.680	85-00	0.0118
1-8	59.76	243.5	18.62	7.87	7.96	0.1344	0. --	---	---
1-9	60.02	261.3	21.72	9.86	9.70	0.1420	1.80	79-30	0.0263
1-10	59.82	280.6	26.87	13.10	13.04	0.1659	1.37	84-00	0.0174
								Ave.	0.0202
2-1	60.37	119.4	7.58	1.57	1.20	0.0843	1.01	49-50	0.0707
2-2	60.24	127.9	8.64	1.91	1.64	0.1005	0.98	59-10	0.0600
2-3	60.20	141.5	9.71	2.38	2.12	0.1059	1.08	63-00	0.0540
2-4	60.17	162.5	11.30	3.18	2.92	0.1106	1.26	66-40	0.0487
2-5	60.05	180.5	12.79	3.99	3.66	0.1128	1.59	66-30	0.0489
2-6	59.90	199.7	14.72	5.10	4.58	0.1150	2.24	64-00	0.0561
2-7	59.65	222.2	17.38	6.70	6.36	0.1290	2.11	71-40	0.0431
2-8	60.00	238.8	19.72	8.15	7.80	0.1367	2.385	73-00	0.0419
2-9	59.50	261.3	24.58	11.11	10.70	0.1568	3.00	74-20	0.0440
2-10	60.00	272.7	27.10	12.82	12.50	0.1680	2.89	77-00	0.0389
								Ave.	0.0426
3-1	60.45	120.3	9.10	1.90	1.50	0.1035	1.164	52-10	0.0804
3-2	60.30	140.3	11.30	2.75	2.28	0.1157	1.538	56-00	0.0780
3-3	60.10	158.3	13.10	3.59	3.00	0.1195	1.972	56-40	0.0787
3-4	59.70	182.3	15.30	4.84	4.18	0.1256	2.44	59-50	0.0734
3-5	60.05	201.3	17.50	6.10	5.32	0.1312	2.97	60-50	0.0735
3-6	60.10	222.3	20.70	7.99	6.96	0.140[illegible]	3.89	6[illegible]-50	0.0790
3-7	60.00	243.3	23.70	9.99	[illegible].04	0.1528	4.28	64-40	0.0726
3-8	59.10	258.1	27.00	12.05	11.32	0.1701	4.12	70-00	0.0619
3-9	58	269.6	shunt	--	13.30	0.1902	--	---	--
								Ave.	0.0758

$$KVA = \frac{1.732}{1000} V_{gen} I_{line}$$

$$KW = (KVA^2 - KVAR^2)^{\frac{1}{2}}$$

$$Angle = \text{arc sin} \frac{KVAR}{KVA}$$

C-2 Continued

Run No.	Freq. cps	V_{gen} (Volts)	I_{line} (amp)	KVA	KVAR	$\frac{VARS}{V^2}$	KW	Angle (deg.)	$\frac{Watts}{V^2}$
4-1	59.87	119.9	11.71	2.44	1.80	0.1252	1.650	47-30	0.1149
4-2	60.27	142.5	14.13	3.49	2.62	0.1290	2.305	48-40	0.1135
4-3	59.98	161.4	15.82	4.33	3.60	0.1381	2.410	56-10	0.0926
4-4	59.50	180.8	18.50	5.79	4.64	0.1421	3.47	53-10	0.1062
4-5	60.28	201.2	20.92	7.30	5.96	0.1480	4.20	54-50	0.1038
4-6	60.54	234.3	25.92	10.52	--	--	--	---	--
								Ave.	0.1096
5-1	59.34	101.7	12.18	2.14	1.44	0.1392	1.585	42-15	0.1532
5-2	60.08	116.6	13.58	2.74	1.96	0.1442	1.912	45-40	0.1410
5-3	59.86	136.6	16.34	3.87	2.80	0.1501	2.655	46-40	0.1421
5-4	60.98	161.1	19.51	5.45	4.00	0.1539	3.69	47-20	0.1418
5-5	60.03	180.9	22.18	6.95	5.30	0.1620	4.50	49-40	0.1379
5-6	59.41	204.1	25.85	9.16	7.20	0.1725	5.69	51-40	0.1365
								Ave.	0.1421

Comparison of Values of Conductance Used to Estimate Conductance of Meters, Etc.

Set No.	Ave. Above	Calibrated Value	Difference Ave.-Cal.	Cal. plus 0.0100	Value Used
1	0.0202	0	0.0202	0.0100	0.0186
2	0.0496	0.0333	0.0163	0.0433	0.0496
3	0.0758	0.0658	0.0100	0.0758	0.0758
4	0.1096	0.0989	0.0107	0.1089	0.1096
5	0.1421	0.1322	0.0099	0.1422	0.1421

C-3 Summary of Data and Calculations for Gamma Network Test

C-3(a) Gamma Network with Transformers
Test Circuit No. 2
Date: 19 February 1954

Ru No.	V_r ave. volts	V_c ave. volts	V_{gen} volts	I_{line} amps.	$X_{c-2} = V_c/I_{line}$ ohms
6-1	149	0.9	153	0	--
6-2	142	33	149	1.73	19.05
6-3	167	74	182	3.66	20.25
6-4	189	127	218	6.20	20.50
6-5	148	0.9	150	0	--
8-1	155	0.5	154	0	--
8-2	140	25.3	145	1.60	15.8
8-3	157	60.5	170	3.63	16.7
8-4	166	101.5	208	6.20	16.4
9-1	149	0.8	150	0.3	--
9-2	151.5	37.2	156	1.8,	20.65
9-3	182	88.6	203	4.1	21.6
9-4	note	--	217	--	--
9-5	182	88.6	202	4.1	21.6
9-6	--	--	217	--	--
10-4	156	0.4	156	0.3	--
10-5	132.3	19.3	134	1.5	12.85
10-6	143.5	42.4	151	3.2	13.20
10-7	164	74.1	177	5.5	13.40
11-1	180.5	0.5	181	0.3	(17.7)
11-2	164.5	24.5	163	1.95	12.58
11-3	167	49.5	174	3.74	13.22
11-4	179.5	80.0	194	6.00	13.31
12-1	181	0.68	181	0.33	--
12-2	169.3	31.7	174	2.0	15.85
12-3	183.7	71.9	195	4.1	17.51
12-4	194.7	109.6	220	6.53	16.80
14-1	214.3	1.03	205	0.3	--
14-2	197.7	47.0	205	2.3	20.45
14-3	187	94.3	210	4.2	22.4
14-4	203	100	226	4.6	21.70

All sets on this page:

Run No.	Nominal Conductance (mho)
any-1	zero
-2	0.0333
-3	0.0666
-4	0.1000

V_r = 171 - 179 - 25
Transformer in resonance with series capacitor.

Conductance same as for runs 1 through 4 in other sets.

Date: 26 February 1954

See F-3(a) original data for set 13. Resonance between the series capacitor and the transformer in one phase in this set. The tests include data to show that this was local resonance.

C-3(b) Gamma Network without Transformers
Test Circuit No. 3
Date: Data Taken 5 March 1954

Run No.	V_{gen} volts	$V_r$ave volts	$V_o$ave volts	I_{phase} amps.	Nominal Cond.	I_p/V_r (mho)	Nominal Suscept.	I_p/V_o (mho)
15-1	189	188	0.4	0	0	--	0.0689	--
15-2	182	180.3	28.2	2.03	0.0110	0.0125	0.0689	0.0720
15-3	205	194.3	61	4.34	0.0222	0.0223	"	0.0711
15-4	229	205.7	98	--	0.0333	--	"	--
16-1	185	184.8	0.4	0	0	--	0.0768	--
16-2	181	179.2	26	2.03	0.0111	0.0113	"	0.0781
16-3	199	190	54.7	4.24	0.0222	0.0223	"	0.0841
16-4	221.5	202	85	--	0.0333	0.--	0.0768	0.--
17-1	186	186	0.4	0	0	--	0.0833	--
17-2	179	176.5	23.8	1.99	0.0111	0.0114	"	0.0836
17-3	194	186	49.5	4.16	0.0220	0.0223	"	0.0841
17-4	215	199	76.7	--	0.0330	--	"	0.--
18-1	187	187	0.4	0	0	--	0.0898	--
18-2	176	175	21.6	1.97	0.0111	0.0113	"	0.0941
18-3	189	182.5	45.5	4.08	0.0222	0.0224	"	0.0899
18-4	209.5	196.7	71.0	--	0.0333	--	"	--

Run No.	15	16	17	18	
$V_r$maximum (volts)	205.7	202	199	196.7	
$V_r$minimum (volts)	180.3	179.2	176.5	175	
$V_r$initial (volts)	188	184.8	186	187	
Overvoltage (volts)	17.7	17.2	13	9.7	$V_r$max - $V_r$init
(%)	9.4	9.3	7.4	5.2	
Undervoltage (volts)	7.7	5.6	9.5	12	$V_r$init - $V_r$min
(%)	4.1	3.0	5.1	6.4	
Range (volts)	25.4	22.8	22.5	21.7	$V_r$max - $V_r$min
(%)	13.5	12.3	12.5	11.8	
Half range (volts)	12.7	11.4	11.3	10.85	
(%)	6.8	6.2	6.3	5.9	
[illegible]	8.03	7.11	6.81	[illegible]	

C-3(c) Gamma Network (Series Capacitor Coupling) Without Transformers
Test Circuit No. 3.

Unbalanced Load Test:

Open-circuit: G_{phase} is infinite......0
One-third load: 0.0111 mho per phase..A
Two-thirds load: 0.0222 mho per phase..B
Full load: 0.0333 mho per phase.......C

Phase order of load
Designation: BC, CA, AB.

Example: Load CAA means G_{bc} = 0.0333 mho, G_{ca} = 0.0111 mho, and G_{ab} = 0.0111 mho.

Frequency for each run = 60.0

Series capacitance chosen so that B = 0.0833 mho per phase at 60 cps. This value is constant for all runs.

Spread = $V_r$maximum - $V_r$minimum (for each run).

Numbers tabulated below are voltages.

Run	V_{gen}	$V_r$bc	$V_r$ca	$V_r$ab	$V_r$ave	Load	Spread	Change from Initial value of $V_r$ave
20-1	190	188.5	189	188.5	188.7	000	0.5	0
20-2	181	177.5	175.5	179.5	177.5	AAA	4.0	11.2 minus
20-3	197	188.5	186.5	187.5	187.5	BBB	2.0	1.2 minus
20-4	218	201	198.5	199.5	199.7	CCC	2.5	11.0 plus
20-5	214	193.5	198.5	205.5	199.3	CCB	12.0	10.6 plus
20-6	211	188.5	197	208	197.5	CCA	19.5	8.8 plus
20-7	217	188.5	204	214.5	202.3	CC0	26.0	13.6 plus
20-8	207	184.5	204.5	207	188.8	CB0	22.5	0.1 plus
20-9	199	182.5	207.5	198.5	196.2	CA0	25.0	7.5 plus
20-10	199	189	215.5	198	200.2	C00	26.5	11.5 plus
20-11	191	185	200.5	190.5	192.2	B00	15.5	3.5 plus
20-12	183	182	189	184.5	185.2	A00	7.0	3.5 minus
20-13	187	186.5	185	187.5	186.2	000	2.5	2.5 minus

Test of Effect of No Frequency Regulation:

Run	21-1	21-2	21-3	21-4	22-1	22-2	22-3	22-4	22-5
Freq.									
cps	60.00	60.00	60.00	60.00	60.00	59.12	58.25	57.08	56.02
RPM	920	925	930	935	920	910	903	891	878
Volts									
$V_r$ave	187	175	186.3	199.5	188	154	154	164.7	172
V_{gen}	188	179	196	217.5	187.5	155	159	180	199
Load	Total conductance of three phases.								
G	0	0.0333	0.0666	0.1000	0	0.0333	0.0666	0.1000	0.13335

C-4 SMOOTH DATA FROM VOLTAGE REGULATION WITH FIXED ELEMENTS

Run	Ave. V_G	Ave. V_L	Ave. I_L	P. F. $\frac{I_R}{\sqrt{I_R^2+I_{cap}^2}}$	G $\frac{I_R\sqrt{3}}{V_L}$	G $\frac{I_L\sqrt{3}}{V_L}$, P.F.	B $\frac{I_c\sqrt{3}}{V_L}$	B $\frac{I_L\sqrt{3}}{V_L}\left(\frac{I_{cap}}{\sqrt{I_R^2+I_{cap}^2}}\right)$
23-1	221	211	7.96	.9931d	.064	.065	.0074	.00
23-2	219.5	209.3	6.65	.98 1d	.0547	.055	.0083	.00194
23-3	216	209.6	4.53	.97 1d	.0373	.0372	.0083	.00128
23-4	215	210	3.1	.95 1d	.0256	.0253	.00825	.0034
23-5	213	209.6	1.5	.9481d	.0124	.01225	.00414	.00194
23-6	269.3	209.6	12.0	.90 1d	.0896	.09	.0434	.0415
23-7	196.5	200.3	1.5	--	--	.01262	--	-.00296
23-8	182.3	189.5	2.9	1.00	.0266	.025	--	-.0096
23-9	198.6	199.6	3.0	.9991d	.0261	.0255	.0087	-.0052
23-10	213.6	210.2	3.2	.9881d	.0252	.0261	.00495	.0046
23-11	233	219.8	3.6	.8451d	.0249	.0265	.0158	.0104
23-12	254	221.8	4.9	.61 1d	.025	.0264	.0328	.0277
23-13	269.3	217	6.6	.4251d	.0252	.0267	.0515	.0455
23-14	279	207.3	8.9	.33 1d	.0243	--	.0697	--
23-15	290.3	196.7	11.0	.2531d	.0254	--	.0978	--
23-16	191	197	.33	.98 1g	.0044	.00218	-.00088	-.00192
23-17	200.3	205	.37	1.00	.0042	.00281	--	-.00137
23-18	211.1	210.3	.33	.98 1d	.00412	.0026	-.000825	-.00038
23-19	212.2	213	.4	.9921d	.00407	.00324	.000814	.00034
23-20	220.2	216.5	.5	.7071d	.004	.00356	.004	.00182
23-21	227.7	220.5	.73	.3861d	.00393	.00404	.00944	.00418
23-22	235.8	224.1	1.4	.2551d	.00386	.0050	.0147	.00933
23-24	258.3	225.2	3.95	.1151d	.00335	--	.0331	--
23-25	270.3	218.7	6.12	.0761d	.00396	--	.0515	--
23-26	280.3	212.5	7.8	.06 1d	.00407	--	.0668	--
23-27	288.9	201.8	10.02	.0481d	.0043	--	.0906	--
23-28	293	197.7	10.83	.0441d	.00438	--	.0933	--
23-29	183	188.3	1.6	1.00	.01388	.0134	--	-.00636
23-30	193.3	196.7	1.67	1.00	.0132	.0124	--	-.00454
23-31	211.3	209.5	1.8	--	--	.0149	--	--
23-32	230.8	219.8	2.2	.7451d	.0158	.0153	.0142	.00815
23-33	242.7	223.3	3.0	.56 1d	.01477	.0163	.02175	.0167
23-34	254.7	222.8	4.05	.42 1d	.0148	.0162	.0319	.027
23-35	268.8	217.8	6.25	.2841d	.01515	--	.051	--
23-36	279.2	209.2	8.3	.1961d	.0141	--	.0705	--
23-37	290.5	197.3	10.88	.1331d	.01315	--	.0984	--
23-38	185.3	188.2	4.6	1.00	.0396	.0414	--	-.00895
23-39	199.2	198.5	4.86	1.00	.0401	.042	--	-.00518
23-40	219.7	211.8	5.36	.9841d	.0405	.0436	.0082	.0046
23-41	243.5	218.3	5.97	.8481d	.0405	.0432	.0254	.0193
23-42	251.5	218.3	6.42	.7761d	.0405	.0432	.0329	.027
23-43	260.8	216.8	7.10	.6921d	.0406	.0426	.0425	.0373
23-44	268.2	212.8	8.01	.5951d	.0406	.0424	.055	.0495
23-45	279.8	202.8	9.79	.4581d	.0404	.0418	.0784	.0724
23-46	288.5	194.5	11.59	.3781d	.0401	--	.0982	--
23-47	296.2	181.8	13.45	.3071d	.0405	--	.126	--
23-48	195.5	194.7	6.2	--	.052	.0546	--	-.0077
23-49	201.5	199.2	6.27	--	.0522	.0542	--	-.0057
23-50	226.2	212	6.72	.9821d	.0522	.0544	.0098	.0081
23-51	231.8	214.7	6.87	.9641d	.0522	.0542	.0145	.0115
23-52	238.5	216.7	7.07	.9431d	.0521	.0539	.0184	.017

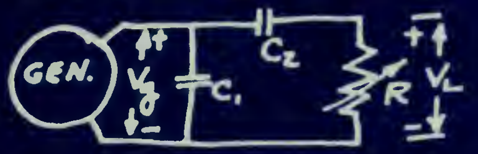
C-4 SMOOTH DATA FROM VOLTAGE REGULATION WITH FIXED ELEMENTS

Run	Ave. V_G	Ave. V_L	Ave. I_L	P.F. $\frac{I_R}{\sqrt{I_R^2+I_{cap}^2}}$	G $\frac{I_R\sqrt{3}}{V_L}$	G $\frac{I_L\sqrt{3}}{V_L}\times P.F.$	B $\frac{I_{cap}\sqrt{3}}{V_L}$	B $\frac{I_L\sqrt{3}}{V_L}\left(\frac{I_{cap}}{\sqrt{I_R^2+I_{cap}^2}}\right)$
23-53	249.8	217	7.52	.8661d	.052	.0546	.0299	.0249
23-54	258	214.7	8.07	.7951d	.0522	.0543	.0399	.0351
23-55	270.7	209.5	9.21	.7001d	.0521	.0535	.058	.0543
23-56	279.7	202.8	10.36	.5721d	.0522	.0538	.075	.0704
23057	287.3	190.5	12.04	.4641d	.0527	.0548	.1005	.095
23-58	294.3	181.8	13.79	.3861d	.049	--	.117	--
23-59	203.7	199.7	7.17	--	.0617	.062	--	-.0065
23-60	214.2	205.7	7.39	.9991d	.0616	.0622	.00169	.0018
23-61	226.7	211.7	7.67	.99 1d	.0615	.062	.0082	.00983
23-62	239.5	213.8	7.95	.96 1d	.0617	.062	.0179	.01835
23-63	246.8	215.2	8.23	.93 1d	.0615	.0616	.025	.0243
23-64	259	213	8.85	.8341d	.0611	.0619	.0406	.0377
23-65	270.8	207.8	9.7	.7321d	.0616	.0609	.0577	.0533
23-66	277.8	201.8	10.78	.6441d	.0615	.0613	.0732	.0710
23-67	286.2	192.3	12.22	.5441d	.0616	.0616	.0955	.0912
23-68	291.2	185	13.32	.4821d	.0616	.0624	.1125	.108
23-69	295	180	14.09	.4441d	.0617	--	.1249	--
23-70	207.3	202	8.28	--	.0678	.0705	--	-.00742
23-71	217.5	207.2	8.49	--	.0678	.0705	--	-.00037
23-72	234.8	212.8	8.87	.985	.0683	.071	.0132	.0125
23-73	248	213.3	9.21	.9461d	..0683	.0705	.0252	.0251
23-74	260.7	211.2	9.86	.8581d	.0682	.0725	.0410	.0361
23-75	268.7	206.2	10.47	.7661d	.0678	.0704	.0571	.0527
23-76	278.3	197.3	11.65	.65 1d	.0677	.0791	.0791	.065
23-77	288.5	184.3	13.39	.5351d	.0686	.069	.1083	.105
23-78	293	179.2	14.31	.4821d	.0681	.0712	.124	.119
23-79	217.8	205.7	10.30	--	.081	.036	--	-.0087
23-80	232.3	211.2	10.47	.9951d	.0821	--	.00821	--
23-81	243.8	212	10.77	.98 1d	.0824	.--	.01715	--
23-82	253.7	212	10.77	.94 1d	.0815	--	.0294	--
23-83	261.7	209.2	11.09	.89 1d	.0812	--	.0414	--
23-84	270	203.3	11.55	.82 1d	.0815	--	.0572	--
23-85	278	197	12.40	.7381d	.0816	--	.0746	--
23-86	287	186.7	13.67	.63 1d	.0816	--	.1005	--
23-87	294.3	177	14.93	..5471d	.0814	--	.1248	--
23-88	226.7	209.2	11.40	--	.094	--	--	--
23-89	237.7	211.3	11.53	.9991d	.0939	--	.00903	--
23-90	249.2	211.2	11.67	.9821d	.0939	--	.0181	--
23-91	259	208.8	11.91	.9421d	.0938	--	.0336	--
23-92	270	203.5	12.43	.8741d	.0938	--	.0521	--
23-93	277.7	195.5	13.10	.7951d	.0936	--	.0716	--
23-94	290	181.2	14.70	.6231d	.0938	--	.118	--

APPENDIX D

SAMPLE CALCULATIONS

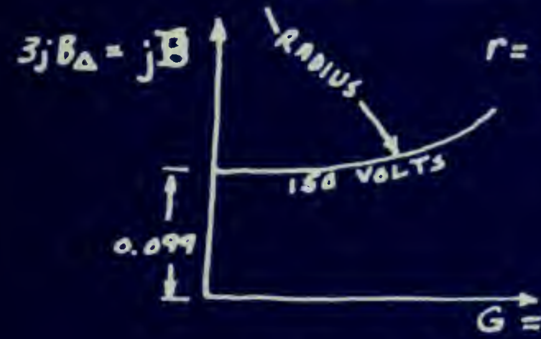
D-1 DETERMINATION OF CIRCUIT PARAMETERS FOR GAMMA NETWORK



DESIGN FOR $V_L = 150^{V}$

$$B_1 = 2\pi f C_1 \qquad (6)$$

$$X_2 = \frac{1}{2\pi f C_2} \qquad (7)$$



r = RADIUS MEASURED ON EXPERIMENTALLY DETERMINED VOLTAG MAP

$$r \approx 0.224 \ \ KVA/V^2 \qquad (8)$$

$$\frac{VARS}{V^2} = 3B_\Delta = 6\pi f C\Big|_{f=60} = 1131\,C$$

$$\frac{WATTS}{V^2} = 3G_\Delta \qquad (9)$$

$$\frac{1}{0.224} = 4.48^{\Omega}$$

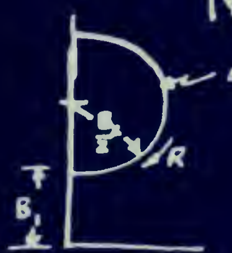
$$1131\,C_1 = 0.099$$

$$C_{1_\Delta} = \frac{99 \times 10^{-3}}{1131} = 87.5\,\mu f/\text{phase} \quad \Delta\text{-CONNECTED}$$

$$Y_G = 3\left[\frac{R}{R^2+X_2^2} + j\left(B_1 + \frac{X_2}{R^2+X_2^2}\right)\right] \qquad (10)$$

V_G is a function of Y_G ← READ V_G FROM VOLTAGE MAP (11)

$$|V_L| = \left|\frac{R}{\sqrt{R^2+X_2^2}}\right| |V_G| \qquad (12)$$



SOLVE (10), (11), & (12) Simultaneously.
TRIAL & ERROR SOLUTION REQUIRED

1st Trial. $R = 50^{\Omega}$ $\quad X_2 = 20^{\Omega}$

$$R^2+X_2^2 = |50-j20| = (53.8^{\Omega})^2 = 2900^{\Omega^2}$$

$$\sqrt{R^2+X_2^2} = 53.8$$

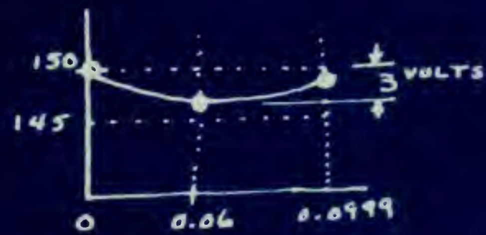
$$\tfrac{1}{3}Y_G = +j0.033 + \frac{50}{2900} + j\frac{20}{2900}$$

$$Y_G = 0.0518 + j0.1197$$

→ $V_G = 193^{V}$ ← FROM MAP

$$V_L = \frac{50}{53.8} \times 193 = 179 \text{ VOLTS}$$

TRIAL	R	X_2	$\lvert R-jX_2 \rvert$	$R^2+X_2^2$	Y_G	V_G	V_L
2	50	15	52.2	2725	.0550+j.1155	179 V	171.5 V
3	50	10	50.9	2600	.0577+j.1105	153 V	150.4 V
	30	10	31.6	1000	0.090+j0.129	180 V	171 V
4	30	8	31.1	964	0.0934+j0.1239	148 V	143 V
5	30	8.5	31.18	972.2	0.0925+j0.1253	155 V	149.1 V
	50	8.5	50.6	2572	0.0584+j0.1089	149 V	147 V



VARIATION = $\frac{3}{150}$ = 2 %

Ok for Trial Solution

$$X_2 = 8.6\ \Omega = \frac{1}{2\pi f C_2} = \frac{1}{377 C_2}$$

$$C_2 = \frac{1}{377 \times 8.6} = 312\ \mu f / \text{phase}$$
(Δ-connected)

Appendix E

SUPPLEMENTARY DISCUSSION

None.

APPENDIX F

ORIGINAL DATA RECORDS

F-1 Machine Data

Name Plate Data of Induction Machine and Driving Motor

Induction Motor, Westinghouse Type CS MIT No. 704
Frame 485C Serial 4884645 Style 89C210 7.5 H.P.
220 volts, 60 cycle, 3 phase, 50° C. temp. rise 100% load 1 hr.
RPM 1710 - 1130 - 860 - 570
Poles 4 - 6 - 8 - 10
Amperes 19.7 - 19.3 - 25.3 - 33.8
Operated as induction generator with 8 poles 900 - 1000 RPM

Direct-Current Motor, Shunt Wound, General Electric
MIT No. 37 Form A17 Serial 930404 Type RF10A
220 volts, 30.4 amperes, 7.5 open intermittent H.P.
400/1350 RPM 50° C. temp. rise 2 hrs.
Operated as D-C shunt motor to drive induction generator.

F-2 Original Data for Induction Generator Terminal Characteristic — Date: 21 December 1953

Test Circuit: No. 1

Run No.	f cps	Gener. Voltages V_{ab}	V_{bc}	V_{ca}	Line Currents I_a	I_b	I_c	KVAR Read	KVAR	D-C Motor Volts	Amperes	Calibrated G (Mho)	
1-1	59.91	118.2	117.0	116.8	6.55	6.10	7.45	0.164	1.312	233	-- -	0	
1-2	60.02	141.0	141.0	141.0	8.45	8.00	9.55	0.257	2.056	233	-- -	"	
1-3	60.05	160.0	159.7	160.8	9.72	9.23	11.03	0.342	2.736	233	4.6	"	
1-4	59.99	178.9	179.2	180.0	11.09	10.47	12.59	0.435	3.48	233	5.0	"	
1-5	59.98	199.6	201.7	202.5	12.95	12.31	14.71	0.578	4.62	233	5.6	"	
1-6	59.74	218.0	220.1	222.1	14.52	14.53	17.36	0.780	5.34	233	6.2	"	
1-7	59.84	240.1	242.1	244.7	17.36	17.38	20.80	0.969	7.75	233	7.3	"	
1-8	59.76	241.0	243.7	246.2	17.45	17.51	20.89	0.388	7.96	233	7.2	"	Changed KVAR
1-9	60.02	258.1	261.7	264.0	20.43	20.27	24.47	0.485	9.70	233	8.3	"	Meter Scale
1-10	59.82	277.7	280.2	284.0	25.63	24.97	30	0.652	13.04	233	10.2	"	
2-1	60.37	120.2	119.1	119.0	7.41	7.21	8.09	0.060	1.20	233	6.0	0.0333	
2-2	60.24	127.8	127.8	128.0	8.40	8.20	9.32	0.082	1.64	233	6.2	"	
2-3	60.20	141.0	141.6	142.0	9.31	9.30	10.54	0.106	2.12	233	7.2	"	
2-4	60.17	161.8	161.8	164.1	10.98	10.79	12.13	0.146	2.92	233	8.6	"	
2-5	60.05	179.6	180.2	180.5	12.33	12.25	13.78	0.183	3.66	233	10.0	"	
2-6	59.90	198.0	200.0	201.0	13.75	14.30	16.10	0.239	4.58	233	11.9	"	
2-7	59.65	220.5	222.0	224.0	16.15	16.98	19.10	0.318	6.36	233	14.5	"	
2-8	60.00	238.0	238.5	240.0	18.35	19.10	21.60	0.390	7.80	233	16.8	"	
2-9	59.50	259.0	261.0	264.0	23.05	23.50	27.20	0.535	10.70	233	20.5	"	
2-10	60.00	270.0	273.0	275.0	25.60	25.70	30.20	0.625	12.50	233	22.6	"	
3-1	60.45	121.0	120.0	120.0	8.70	8.50	10.20	0.075	1.50	233	8.0	0.0658	
3-2	60.70	140.0	140.0	141.0	10.40	11.20	12.20	0.114	2.28	233	10.5	"	
3-3	60.10	158.0	158.0	160.0	12.05	13.00	14.30	0.150	3.00	233	12.6	"	
3-4	59.70	181.0	182.0	184.0	14.00	15.30	16.75	0.209	4.18	233	16.1	"	
3-5	60.05	200.0	201.0	203.0	16.20	17.25	19.00	0.266	5.32	229	19.5	"	
3-6	60.10	221.0	222.0	224.0	18.75	19.85	21.90	0.348	6.96	228	23.6	"	
3-7	60.00	241.0	243.0	246.0	22.00	23.00	25.90	0.452	9.04	227	28.9	"	
3-8	59.10	257.5	257.5	249.5	25.70	26.40	30.00	0.562	11.32	226	33.2	"	
3-9	-- --	269	-	-	-	-	-	0.690	13.80	?	about 38	"	

F-2 Continued Data

Run No.	f cps	Gener. Voltages V_{ab}	V_{bc}	V_{ca}	Line Currents I_a	I_b	I_c	KVAR Read	KVAR	D-C Motor Volts	Amperes	Calibrated G (Mho)
4-1	59.87	120.0	119.9	119.9	10.00	11.65	12.42	0.090	1.80	231	10.9	0.0989
4-2	60.27	143.3	142.0	141.3	12.98	14.16	15.20	0.131	2.62	230	14.4	"
4-3	59.98	160.1	160.5	163.7	14.93	16.17	17.36	0.180	3.60	230	18.1	"
4-4	59.50	179.9	180.7	181.9	17.17	18.43	20.00	0.232	4.64	229	22.5	"
4-5	60.28	199.8	201.2	202.6	19.42	20.75	22.80	0.298	5.96	228	28.0	"
4-6	60.54	232.5	233.7	236.8	24.20	25.37	28.31	0.445	---	226	39.6	"
5-1	59.34	102.0	101.0	101.8	11.94	12.01	12.58	0.072	1.44	232	10.1	0.1322
5-2	60.08	119.9	116.0	115.8	12.80	13.58	14.38	0.098	1.96	231	13.6	"
5-3	59.86	136.9	135.9	136.9	15.17	16.08	17.79	0.140	2.80	230	17.2	"
5-4	60.98	161.6	160.2	161.7	18.01	19.48	20.87	0.200	4.00	229.5	23.9	"
5-5	60.03	179.7	180.0	183.0	20.60	21.97	23.98	0.265	5.30	228	30.1	"
5-6	59.41	203.6	203.8	206.1	24.21	25.37	27.97	0.360	7.20	226	39.6	"

F-3 Original Data for Gamma Network Tests (Series Capacitor Coupling)

F-3(a) Gamma Network With Transformers
Test Circuit No. 2
Date: 19 February 1954, Runs 6-1 through 8-4. 26 February 1954 , Sets 9 through 14.

Run No.	V_{gen} volts	$V_r ca$ volts	$V_r bc$ volts	$V_r ab$ volts	$V_c ca$ volts	$V_c bc$ volts	$V_c ab$ volts	I_{ca} amps	Ibc amps	I_{ab} amps	Freq. cps	V_{dc} volts	I_{arm} amps	I_{fld} amps	Conduct. mho
6-1	153	149	149	148	1.1	1.0	0.6	0	0	0	59.95	232	3.8	0.5	0
6-2	149	142	144	142	33.0	35.0	29.5	1.7	1.7	1.8	60.07	232	7.0	0.5	0.0333
6-3	182	166	166	170	76.5	70.5	74.0	3.55	3.68	3.75.	60.02	230	14.0	0.4	0.0666
6-4	218	185.5	190	192	131	122	129	5.92	6.3	6.3	60.20	228	25.2	0.4	0.0987
6-5	150	146.5	148	150	1.1	1.0	0.6	0	0	0	60.00	232	3.6	0.5	0
7-1	154	148	154	153	5.5	5.0	5.3	0	0	0	60.06	234	4.4	0.5	0
7-2	Voltage collapse. Series capacitive reactance set at nominal value of 8.6 ohms.														0.0333
8-1	154	151.5	159	157	0	0.6	0.9	0	0	0	60.07	234	4.0	0.5	0
8-2	145	140	147.5	140	27.6	24.0	27.5	1.6	1.6	1.6	60.06	234	7.1	0.5	0.0333
8-3	170	158	165	156.5	58.8	62.0	85.0	3.6	3.7	3.6	60.09	232	13.1	0.5	0.0665
8-4	208	182	190	163	102	101	152	6.1	6.3	5.5	60.09	230	23.3	0.5	0.0998
9-1	150	147	151	149	1.0	0.6	0.8	0.5	0	0.5	60.02	232	4.2	0.5	0
9-2	156	150.5	154	150	39.5	34.2	38.0	1.8	1.8	1.8	60.08	231	8.2	0.5	0.0333
9-3	203	177.5	186	182	94	84	88	4.0	4.1	4.1	60.00	230	16.9	0.5	0.0663
9-4	217	171	179	25	151	123	194	5.7	6.0	1.5	60.00	230	17.9	0.5	0.0997
9-5	202	178	186	182	93	84	88	4.0	4.1	4.1	60.01	230	16.9	0.5	0.0663
9-6	217	171.5	179	25	151	123	193.5	5.7	6.0	1.5	60.00	229	17.9	0.5	0.0997
10-1	132	128	130.5	130.5	20.4	16.0	19.5	1.6	1.6	1.6	60.08	232	6.6	0.5	0.0333
10-2	148	138.5	142.5	141.5	43.5	39.3	43.0	3.2	3.2	3.2	59.99	230	10.8	0.5	0.0666
10-3	179	172	165	165.5	77	72	76	5.45	5.65	5.62	60.10	228	20.0	0.5	0.1000
10-4	156	156	162	151.5	0.5	0.3	0.5	0.5	0	0.5	60.09	232	4.1	0.5	0
10-5	134	130.5	136	130.5	20.4	17.3	20.2	1.5	1.5	1.5	60.08	232	6.5	0.5	0.0333
10-6	151	141.0	144.5	144	44.0	39.8	43.4	3.2	3.2	3.22	60.04	231	10.9	0.5	0.0666
10-7	177	161	167	163.5	76	72	74.3	5.35	5.55	5.57	59.92	230	19.4	0.5	0.1000

F-3(a) Data continued.

Run No.	V_{gen} volts	$V_{r}ca$ volts	$V_{r}bc$ volts	$V_{r}ab$ volts	$V_{c}ca$ volts	$V_{c}bc$ volts	$V_{c}ab$ volts	I_{ca} amps	I_{bc} amps	I_{ab} amps	Freq. cps	V_{dc} volts	I_{arm} amps	I_{fld} amps	Conduct. mhos
11-1	181	178.5	181.5	181	0.6	0.5	0.5	0.5	0	0.5	60.03	232.5	4.6	0.50	0
11-2	163	162.5	166	163.5	25.7	22.9	25.0	1.95	1.95	1.95	60.07	232	8.8	0.50	0.0333
11-3	174	165	169.5	166.5	51.2	46.5	51.0	3.7	3.8	3.8	59.99	231	14.0	0.49	0.0666
11-4	194	177.5	182.5	178	83	78	80	5.85	6.1	6.0	60.06	230	22.7	0.47	0.1000
12-1	181	179	183	181.5	0.8	0.6	0.7	0.2	0	0.6	59.97	234.5	4.6	0.50	0
12-2	174	166.5	171.5	170	33.0	29.8	32.5	2.0	2.0	2.0	59.98	232.5	9.1	0.50	0.0333
12-3	195	182	187	182	70	76	69.6	4.08	4.10	4.1	60.03	232	16.5	0.49	0.0666
12-4	220	192	198	194	112	106	111	6.36	6.65	6.6	60.08	230	27.1	0.48	0.1000
13-1	180	179	183.5	182	1.1	0.8	0.9	0.5	0	0.5	59.98	234.5	4.5	0.50	0
13-2	185	176.5	181.5	179.5	46.5	39.9	44.0	2.0	2.05	2.1	60.03	233.5	9.9	0.50	0.0333
13-3	214	189	198	193.5	100.5	89	95	4.21	4.4	4.3	60.01	231	18.6	0.50	0.0666
13-4	222	174	183	35	158.5	128	195	5.79	6.15	1.8	60.05	231	18.5	0.49	0.1000
13-1A	180	179	181.5	181	1.1	0.8	0.9	0.5	0	0.6	59.97	233.5	4.5	0.50	0
13-3A	215	189	198	194.5	101	90	95	4.25	4.4	4.4	60.08	231	18.8	0.49	0.0666
13-4A	222	174	183	40	158	127	195	5.80	6.10	1.8	60.09	230	18.6	0.49	0.1000
13-4B	213	28	182	213.5	203	126	1.1	1.50	6.05	---	59.99	231	12.2	0.49	note
13-5A	212	20	160.5	25	206	167	194	2.0	7.2	2.0	60.00	232	13.9	0.49	0.1335

Note: Run 13-4B. Conductance of phases ca and ab was 0.0333 each. Phase ab was open-circuited.

Run No.	13-1A	13-3A	13-4A	13-4B	13-5A
I_{circ} (amp.)	0	1.0	4.0	0	3.8

14-1	205	202	206	205	1.2	0.8	1.1	0.5	0	0.5	60.00	232	5.0	0.50	0
14-2	205	194	200	199	51.1	44	46	2.2	2.3	2.3	60.05	232	11.5	0.50	0.0332
14-3	210	183	193	185	100	90	93	4.1	4.4	4.6	58.8	230	17.9	0.50	0.0666
14-4	226	198	207	204	106	94	99	4.4	4.6	4.6	60.00	230	20.5	0.48	0.0666
14-5	219	40	188	40	206	130	193	1.8	6.25	1.8	60.00	230	13.8	0.50	0.0999

F-3(b) Gamma Network (Series Capacitor Coupling) without Transformers
Test Circuit No. 3 Note: Data for three phases tabulated
Date: 5 March 1954 vertically.

Run No.	V_{gen} volts	V_r volts	V_c volts	I_{line} amps.	Freq. cps	Nominal Conduct. mho	Nominal Suscept. mho	D-C Motor V_{dc}	I_{arm}
15-1	189	187	0.5	0	60.08	0	0.0698	231	4.5
phase ca.		.188.....	0.4	0		0	"		
phase ab.		.189.....	0.4	0		0	"		
15-2	182	179.5	29.2	3.52	60.01	0.0110	"	230	9.8
		180.5	26.2	3.51		0.0110	"		
		181	29.4	3.53		0.0110	"		
15-3	205	194.5	62	7.68	60.00	0.0222	"	228	17.9
		193.5	57	7.38		0.0221	"		
		195	62	7.52		0.0222	"		
15-4	229	204.5	100	shunt	60.15	0.0332	"	226	29.2
		206	92	"		0.03325	"		
		206.5	102	"		0.03335	"		
16-1	185	184	0.4	0	60.05	0	0.0768	232	4.4
		184.5	0.5	0		0	"		
		186	0.5	0		0	"		
16-2	181	180	27.0	3.53	60.00	0.0111	"	231	9.5
		177.5	24.5	3.51		0.0111	"		
		180	26.5	3.53		0.0111	"		
16-3	199	190	56.8	7.43	60.00	0.0222	"	229	17.1
		188.5	51.0	7.22		0.0221	"		
		191	55.8	7.38		0.0221	"		
16-4	221.5	201.5	88	shunt	60.00	0.0333	"	227	27.8
		202	82	"		0.03335	"		
		202	85	"		0.03333	"		
17-1	186	188	0.5	0	59.99	0	0.0833	231	4.4
		175.5	0.4	0		0	"		
		185.5	0.4	0		0	"		
17-2	179	175.5	22.5	3.43	60.00	0.0111	"	230	9.3
		175.5	22.1	3.42		0.0111	"		
		176	22.0	3.50		0.0111	"		
17-3	194	185.5	51.8	7.29	60.00	0.0222	"	229	16.4
		185.5	46.5	7.15		0.02225	"		
		186.5	50.5	7.22		0.02225	"		
17-4	215	199.5	80	shunt	60.00	0.0333	"	228	25.6
		198.5	74	"		0.03335	"		
		200	81	"		0.03333	"		

F-3(b) Data continued.

Run No.	V_{gen} volts	V_r volts	V_c volts	I_{line} amps.	Freq. cps	Nominal conduct. mho	Nominal Suscept. mho	D-C V_{dc}	Motor I_{arm}
18-1	187	188	0.5	0	60.00	0	0.0898	232	4.3
		187	0.4	0		0	"		
		187	0.4	0		0	"		
18-2	176	173.5	22.5	3.40	60.00	0.0111	"	231	9.0
		173.5	20.3	3.40		0.0111	"		
		176	22.0	3.45		0.0111	"		
18-3	189	182	47	7.14	60.00	0.0222	"	230	15.7
		182	42.6	6.98		0.0222	"		
		184	46.7	7.10		0.0222	"		
18-4	209.5	195	73.5	shunt	60.00	0.0333	"	229	25.6
		195	67	"		0.03335	"		
		197	72.5	"		0.03335	"		

F-3(c) Preliminary data. Test Circuit No. 3, 12 March 1954.

Run No.	V_{gen} volts	V_r volts	V_c volts	I_{line} amps.	Freq. cps	Nominal conduct. mho	Nominal Suscept. mho	D-C V_{dc}	Motor I_{arm}
19-1	219	202	83	shunt	60.00	0.0333	0.0833	228	27.6
		199.5	74	"		0.03335	"		
		201	80	"		0.03335	"		
19-2	197.5	188.5	51	7.34	60.00	0.0222	"	230	18.8
		187	48	7.23		0.02225	"		
		189.5	50	7.31		0.02225	"		
19-3	181	178	24.2	3.47	60.00	0.0111	"	232	9.5
		176.5	24.0	3.45		0.0111	"		
		178.5	24.3	3.45		0.0111	"		
19-4	189	188	0.4	0	60.00	0	"	233	4.5
		187.5	0.5	0		0	"		
		190	0.5	0		0	"		
19-5	187	191	0.4	2.08	60.00	0	"	232	6.2
		181.5	0.5	0		0	"		
		183	25.1	2.20		0.0111	"		
19-6	193	200	0.5	4.11	60.00	0	"	232	8.3
		187.5	0.5	0		0	"		
		185	53	4.20		0.0221	"		
19-7	187	187.5	25.8	5.27	60.00	0.0111	"	232	11.6
		179	24.8	3.59	60.00	0.0111	"		
		181	50.0	5.48		0.02225	"		
19-8	200	202.5	28	7.22	60.00	0.0111	"	231	14.6
		190	25.9	3.88		0.0111	"		
		183.5	80	7.70		0.03335	"		

Balanced load for runs 19-1 to 19-4.
Phase ab load unbalanced for runs 19-5 to 19-8.
Ammeters reconnected after this set so that they indicated only current in one particular phase.

F-3(c) Original Data, Gamma Network (Series Capacitor Coupling) Without Transformers, Unbalanced Load Test and Test Without Frequency Regulation.

See previous page for preliminary data for this test.

Test Circuit No. 3. Date: 12 March 1954.

Runs 20-1 to 20-13 are the unbalanced load runs. The load was increased by increments of 0.011 mho in each phase with the three phases balanced. The load was removed by decreasing the load in each phase in succession by the same increments. Phase ab was unloade to open-circuit while the other two phases were fully loaded, then the other two phases were unloaded one at a time.

Set 21 is for balanced conditions and with the frequency maintained at 60 cps. Set 22 is for balanced conditions, but the frequency was not regulated.

Run No.	20-1	20-2	20-3	20-4	20-5	20-6	20-7	20-8
G_{bc} (mho)	0	0.0111	0.0222	0.0333	0.0333	0.0333	0.0333	0.0333
G_{ca} (mho)	0	0.0111	0.0222	0.0332	0.0332	0.0332	0.0332	0.0221
G_{ab} (mho)	0	0.0111	0.0222	0.0333	0.0222	0.0112	0	0
B_{bc} (mho)	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833
B_{ca} (mho)	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833
B_{ab} (mho)	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833
$V_r$bc (volts)	188.5	177.5	188.5	201	193.5	188.5	188.5	184.5
$V_r$ca (volts)	189	175.5	186.5	198.5	198.5	197	204	204.5
$V_r$ab (volts)	188.5	179.5	187.5	199.5	205.5	208	214.5	207
V_{gen} (volts)	190	181	197	218	214	211	217	207
$V_o$bc (volts)	0.44	25.2	54	80	77.5	74	75.5	73.5
$V_o$ca (volts)	0.48	24.7	51	81	81	80	82	57
$V_o$ab (volts)	0.53	24.9	54	84	80	29.0	0.60	0.57
Freq. (cps)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
RPM	920	925	930	935				
I_{bc} (amps)	0	1.99	4.19	6.72	6.48	6.30	6.42	6.20
I_{ca} (amps)	0	2.00	4.22	6.62	6.52	6.62	6.78	4.60
I_{ab} (amp.)	0	2.02	4.25	6.76	4.60	2.40	0	0
V_{dc} (volts)	232	231	230	228	229	230	230	231
I_{arm} (amp.)	4.5	9.5	16.7	27.25	23.4	20.6	18.5	15.4

F-3(c) Data continued.

Run no.	20-9	20-10	20-11	20-12	20-13
G_{bc} (mho)	0.0333	0.0333	0.0222	0.0111	0
G_{ca} (mho)	0.0111	0	0	0	0
G_{ab} (mho)	0	0	0	0	0
B_{bc} (mho)	0.0833	0.0833	0.0833	0.0833	0.0833
B_{ca} (mho)	0.0833	0.0833	0.0833	0.0833	0.0833
B_{ab} (mho)	0.0833	0.0833	0.0833	0.0833	0.0833
$V_{r}bc$ (volts)	182.5	189	185	182	186.5
$V_{r}ca$ (volts)	207.5	215.5	200.5	189	185
$V_{r}ab$ (volts)	198.5	198	190.5	184.5	187.5
V_{gen} (volts)	199	199	191	183	187
$V_{c}bc$ (volts)	72.5	74.5	53	25.2	0.42
$V_{c}ca$ (volts)	25.0	0.56	0.50	0.48	0.48
$V_{c}ab$ (volts)	0.55	0.55	0.52	0.51	0.52
Freq. (cps)	60.0	60.0	60.0	60.0	60.0
I_{bc} (amp.)	6.15	6.32	4.15	2.00	0
I_{ca} (amp;)	2.35	0	0	0	0
I_{ab} (amp.)	0	0	0	0	0
V_{dc} (volts)	231	231.5	232	232	232
I_{arm} (amp.)	12.6	10.8	8.3	6.0	4.3

F-3(c) Data continued.

Run No.	Frequency Regulated........				Frequency Not Regulated...........				
	21-1	21-2	21-3	21-4	22-1	22-2	22-3	22-4	22-5
Load (mho)									
G_{bc}	0	0.0111	0.0222	0.0333	0.	0.0111	0.0222	0.0333	0.0440
G_{ca}	0	0.0111	0.0222	0.0333	0	0.0111	0.0222	0.0333	0.0442
G_{ab}	0	0.0111	0.0222	0.0334	0	0.0111	0.0222	0.0334	0.04415
B_{bc}	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833
B_{ca}	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833
B_{ab}	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833	0.0833
Volts									
$V_r bc$	186.5	177	187.5	201	187.5	153	152.5	165.5	172.5
$V_r ca$	185.5	175.5	185.5	197.5	186.5	151	151.5	162.5	170
$V_r ab$	188.5	172.5	186	199.5	190	158	157	166	172
V_{gen}	188	179	196	217.5	187.5	155	159	180	199
$V_c bc$	0.41	24.9	55	80	0.42	21.8	43.5	68	100
$V_c ca$	0.42	24.1	53	81	0.45	21.0	42.5	68	98
$V_c ab$	0.52	24.7	54	86	0.52	21.4	43.0	76	104
V_{dc}	233	232	231	228	233	233	232	230	229
Amp.									
I_{bc}	0.	2.03	4.30	6.79	0	1.85	3.45	5.60	7.69
I_{ca}	0	2.00	4.23	6.60	0	1.85	3.38	5.50	7.53
I_{ab}	0	2.02	4.29	6.72	0	1.85	3.42	5.60	7.69
I_{arm}	4.4	9.3	16.5	27.0	4.4	7.5	11.5	18.7	26.5
Freq. (cps)	60.00	60.00	60.00	60.00	60.00	59.12	58.25	57.08	56.02
RPM	920	925	930	935	920	910	903	891	878

Values of B are nominal at 60 cps and are tabulated as such to emphasize that series capacitance is constant. Effective value for last four runs should be reduced by frequency ratio. $B = 6.28\, f\, C$

F-4 OBSERVED DATA OF VOLTAGE REGULATION WITH FIXED ELEMENTS

	Generator Terminals			Load Terminals				
Run	Vab	Vbc	Vca	Vab	Vbc	Vca	Ixb	Ixc
23-1	221	216	223	213	210.5	209.5	70	70
23-2	219	216	220	211	209.5	208.5	70	70
23-3	216	215	216	211.5	209.5	208	70	70
23-4	215	213	215.5	211.5	210.5	208	70	70
23-5	212	213	214	212	210	207	70	70
23-6	268	270	270	210	208	211	120	120
23-7	195	197	197.5	200.5	200	200.5	70	70
23-8	182	183	182	188.5	185	195	70	70
23-9	198	199	199	199	197	203	70	70
23-10	213	214	214	210.5	208	212	70	70
23-11	232	234	233	220.5	217	222	100	100
23-12	253	255	254	222	219	224.5	110	110
23-13	268	271	269	218	213	220	125	125
23-14	277	280	280	207	205	210	135	135
23-15	288	292	291	195	195	200	150	150
23-16	191	191	191	197	197	197	80	80
23-17	200	200	201	205	205	205	80	80
23-18	210	211.5	212	211	209.5	210.5	90	90
23-19	212	212	212.5	213	211	215	95	95
23-20	219.5	220	221	217.5	215.5	217	100	100
23-21	226	228	229	221.5	219	221	100	100
23-22	234	236.5	237	225	222.5	225	105	105
23-23	248.5	250.5	251	227	225	226.5	120	120
23-24	257	258	260	226	224	225.5	135	135
23-25	269	272	272	219	217.5	219.5	135	135
23-26	278.5	280.5	281.5	212	212	213.5	135	135
23-27	286.5	289.5	290	201	201.5	203	150	150
23-28	291	294	294	197	197	199	150	150
23-29	183	183	183	189	185	191	70	70
23-30	193	194	193	197	194	199	70	70
23-31	211	212	211	210	207	211.5	100	100
23-32	230	231.5	231	220.5	217	222	100	100
23-33	241.5	243.5	243	224	220	226	110	110
23-34	253	256	255	223.5	220	225	115	115
23-35	268	270	268.5	218	215	220.5	125	125
23-36	277.5	281	279	209.5	207.5	212.5	135	135
23-37	289.5	292	290	196.5	195.5	200	150	150
23-38	185	186	185	189	184.5	191	70	70
23-39	198.5	200	199	199	195	201.5	90	90
23-40	199	220	220	212	208.5	214.5	100	100
23-41	243	244.5	243	219	214.5	221.5	110	110
23-42	251	252	251.5	219	214.5	221.5	110	110
23-43	260	262	260.5	217.5	213	220	120	120
23-44	268	268.5	268	213.5	209.5	215	125	125
23-45	279	281	279.5	204	201	203.5	135	135
23-46	287	290	288.5	194	191.5	198	150	150
23-47	295	297.5	296	182	180	183.5	160	160
23-48	194.5	196	195	195	191.5	197.5	80	80
23-49	201.5	202	201	193	197	201.5	90	90
23-50	225	227.5	226	212.5	209	214.5	100	100
23-51	231	233	231.5	215	212	217	105	105
23-52	237.5	239	239	217	214	219	110	110

F-4 OBSERVED DATA OF VOLTAGE REGULATION WITH FIXED ELEMENTS

Run	Motor V	I	f cps	RPM	Load I_R	I_{CAP}	Load Terminals I_A	I_B	I_C	P.F.
23-1	232	20.5	60.1	928	7.8	.79	8.4	7.5	7.8	1.0001d
23-2	232	17.6	60.1	922	6.6	1.0	7.0	6.3	6.65	.9981d
23-3	232	13.4	60.2	921	4.5	1.0	4.9	4.1	4.6	.9981d
23-4	233	10.4	60.0	920	3.1	1.0	3.7	2.7	3.0	.9901d
23-5	233	7.6	59.9	915	1.5	.5	1.9	1.0	1.5	.9881d
23-6	228	30.5	60.2	928	10.85	5.25	12.1	11.8	12.2	.9091d
23-7	233	7.2	60.0	915	--	--	1.9	1.2	1.5	.9741g
23-9	231	9.5	60.0	920	3.0	.1	3.0	2.8	3.2	.9801g
23-10	231	10.5	60.0	918	3.05	.5	3.1	2.9	3.5	.9991d
23-11	230	12.0	60.0	918	3.15	2.0	3.5	3.5	3.9	.93 1d
23-12	229	13.2	60.0	916	3.20	4.20	4.6	4.9	5.15	.69 1d
23-13	229	14.0	60.0	918	3.15	6.45	6.3	6.6	6.8	.5051d
23-14	229	14.4	59.9	915	3.05	8.75	--	8.9	8.9	.--
23-15	229	15.2	60.0	915	2.90	11.10	--	11.1	11.0	--
23-16	231	5.0	60.0	915	.50	.10	1.0	0.0	0.0	.75 1g
23-17	231	5.5	60.0	915	.50	0.0	1.0	0.0	0.0	.9001g
23-18	230	5.8	60.0	911	.50	.10	1.0	0.0	0.0	.9901g
23-19	231	5.8	60.0	911	.50	.10	1.0	0.0	0.2	.9921d
23-20	231	6.0	60.0	911	.50	.50	1.0	0.0	0.5	.892 1d
23-21	231	6.5	60.0	912	.50	1.2	1.0	0.0	1.2	.6951d
23-22	231	6.8	60.0	912	.50	1.9	1.3	1.0	1.0	.5101d
23-23	233	7.5	60.0	912	.50	3.3	0.0	2.8	3.1	--
23-24	231	8.0	60.0	912	.50	4.3	--	3.8	4.1	--
23-25	230	8.8	59.9	912	.50	6.5	--	6.0	6.25	.--
23-26	231	9.5	60.0	911	.50	8.2	--	7.7	7.9	--
23-27	230	10.5	60.0	912	.50	10.35	--	9.95	10.1	--
23-28	230	11.0	60.0	911	.50	11.20	--	10.75	10.92	--
23-29	231	6.6	60.0	915	1.50	0.0	1.6	1.3	1.9	.9021g
23-30	231	7.2	60.0	915	1.50	0.0	1.7	1.4	1.9	.9381g
23-31	231	8.0	60.0	915	--	--	1.8	1.5	2.1	1.00
23-32	232	9.0	60.0	915	2.0	1.8	2.0	2.0	2.5	.8821d
23-33	232	9.6	60.0	915	1.9	2.8	2.9	2.9	3.2	.6981d
23-34	231	10.3	60.0	915	1.9	4.1	3.7	4.1	4.25	.5151d
23-35	231	11.1	60.0	915	1.9	6.4	--	6.2	6.3	--
23-36	232	12.0	60.0	915	1.7	8.5	--	8.3	8.3	--
23-37	231.	12.8	60.0	915	1.5	11.2	--	10.88	10.89	--
23-38	231	11.5	60.0	920	4.3	0.0	4.5	4.9	4.9	.9761g
23-39	232	12.8	60.0	920	4.6	0.0	4.8	4.65	5.15	.9911g
23-40	231	14.6	60.0	920	4.95	1.0	5.08	5.1	5.54	.9931d
23-41	230	16.5	60.0	920	5.10	3.2	5.75	5.85	6.3	.9121d
23-42	230	17.0	60.0	920	5.10	4.15	6.15	6.40	6.72	.8491d
23-43	230	17.5	60.0	920	5.09	5.32	6.80	7.10	7.40	.7511d
23-44	230	17.8	60.0	920	5.00	6.75	7.70	8.05	8.28	.65 1d
23-45	230	18.0	60.0	920	4.73	9.18	9.48	9.89	10.00	.50 1d
23-46	230	18.3	60.0	920	4.50	11.04	--	11.60	11.58	--
23-47	230	18.6	60.0	920	4.25	13.20	--	13.50	13.40	--
23-48	230	14.9	60.0	922	5.85	0.0	6.1	6.0	6.4	.99 1g
23-49	230	15.5	60.0	923	6.00	0.0	6.21	6.1	6.51	.9931g
23-50	230	18.2	60.0	920	6.40	1.2	6.58	6.99	6.99	.9891d
23-51	230	18.5	60.0	920	6.48	1.8	6.79	6.72	7.11	.9791d
23-52	230	19.3	60.0	920	6.51	2.3	6.95	6.95	7.31	.9531d

F-4 OBSERVED DATA OF VOLTAGE REGULATION WITH FIXED ELEMENTS

	Generator Terminals			Load Terminals				
Run	Vab	Vbc	Vca	Vab	Vbc	Vca	Ixb	Ixc
23-53	249	250.5	249.5	218	214	219	110	110
23-54	257	258	259	215	212	217	115	115
23-55	269.5	272	270.5	209	207.5	212	135	135
23-56	279	280	280	202	201.5	205	140	140
23-57	287	288	287	191.5	185	195	150	150
23-58	293	296	294	180.5	180	185	160	160
23-59	203	204	204	200.5	198	200.5	100	100
23-60	213.5	214	215	206.5	203.5	207	100	100
23-61	225.5	227	227.5	212.5	209.5	213	105	105
23-62	238	239.5	240.5	216	212.5	216	110	110
23-63	246	248	246.5	216	213.5	216	110	110
23-64	258.5	259	259.5	214	211	214	120	120
23-65	270	272	270.5	208.5	206.5	208.5	130	130
23-66	276	279	278.5	202	200.5	203	140	140
23-67	285	287.5	286	193	190	194	145	145
23-68	290	291.5	292	186	183	186	150	150
23-69	294	296	295	180	178	182	160	160
23-70	207	208	207	202	199	205	100	100
23-71	217	218	217.5	207	204.5	210	100	100
23-72	233	236	235.5	213	210	215.5	105	105
23-73	247	249	248	213.5	210.5	216	110	110
23-74	259	262	261	211	208.5	214	115	115
23-75	267	270	269	206	20[illegible].5	209	130	130
23-76	277	279	279	197	195	200	140	140
23-77	287	290	288.5	186	182.5	184.5	150	150
23-78	292	293	294	179	176.5	182	160	160
23-79	217.5	218	218	206	203	208	100	100
23-80	231	233	233	212	208.5	213	105	105
23-81	243	245	243.5	213	211	212	110	110
23-82	253	254	254	211.5	210.5	214	115	115
23-83	261	262	262	209	207.5	211	120	120
23-84	269	271	270	203	202	205	130	130
23-85	277	279	278	197	195	199	135	135
23-86	286	289	289	186	185	189	150	150
23-87	293	296	294	176	175.5	179.5	160	160
23-88	225	227	228	210.5	208	209	100	100
23-89	236	233	239	213	210	211	110	110
23-90	247	250	250.5	212	210.5	211	110	110
23-91	258	259	260	209.5	208	209	120	120
23-92	268	271	271	203.5	203	204	120	120
23-93	276	279	278	195.5	195	196	130	130
23-94	289	291	291	181.5	180	182	140	140

F-4 OBSERVED DATA OF VOLTAGE REGULATION WITH FIXED ELEMENTS

Run	Motor V	Motor I	f_{cps}	RPM	Load I_R	Load I_{CAP}	Load Terminals I_A	Load Terminals I_B	Load Terminals I_C	P.F.
23-53	230	20.0	60.0	920	6.51	3.75	7.35	7.50	7.72	.9101d
23-54	230	20.5	60.0	920	6.47	4.95	7.85	8.05	8.30	.8401d
23-55	229	20.6	60.0	920	6.30	7.01	9.00	9.20	9.42	.7001d
23-56	229	20.8	60.0	920	6.11	8.78	10.11	10.40	10.58	.6081d
23-57	229	20.8	60.0	920	5.80	11.05	11.90	12.02	12.19	.5001d
23-58	230	20.6	60.0	920	5.42	12.96	--	13.82	13.75	.--
23-59	230	17.5	60.0	922	7.10	0.0	7.30	7.00	7.22	.9941g
23-60	230	18.7	60.0	923	7.30	.2	7.52	7.20	7.45	1.00
23-61	230	20.2	60.0	922	7.50	1.0	7.82	7.45	7.73	.9381d
23-62	230	21.2	60.0	920	7.60	2.2	8.05	7.75	8.06	.9581d
23-63	230	21.6	60.0	921	7.62	3.1	8.30	8.05	8.35	.931d
23-64	229	22.3	60.0	920	7.51	5.0	8.90	8.65	9.00	.86 1d
23-65	229	22.6	60.0	920	7.39	6.90	9.50	9.60	10.00	.7521d
23-66	229	22.5	60.0	920	7.15	8.51	10.75	10.60	11.00	.6621d
23-67	229	22.4	60.0	919	6.82	10.6	12.18	12.05	12.42	.5601d
23-68	229	22.3	60.0	920	6.58	12.02	13.35	13.12	13.50	.5011d
23-69	229	22.1	60.0	920	6.42	12.96	--	14.01	14.18	--
23-70	230	20.1	60.0	925	7.90	0.0	8.20	8.10	8.55	.9931g
23-71	229	21.4	60.0	925	8.11	0.0	8.4	8.3	8.78	.9981g
23-72	228	23.4	60.0	925	8.38	1.6	8.7	8.8	9.1	.9851d
23-73	228	24.1	60.0	925	8.40	3.10	9.05	9.13	9.45	.942 1d
23-74	228	24.6	60.0	921	8.30	5.00	9.56	9.72	10.3	.8951d
23-75	227	24.6	60.0	920	8.08	6.80	10.28	10.42	10.72	.8001d
23-76	228	24.4	60.0	920	7.71	9.01	11.40	11.70	11.85	.7731d
23-77	228	24.2	60.0	919	7.30	11.52	13.26	13.38	13.52	.5501d
23-78	228	24.2	60.0	919	7.05	12.32	14.20	14.30	14.42	.5151d
23-79	227	24.5	60.0	926	9.60	0.0	9.85	9.72	10.13	.9951g
23-80	227	26.4	60.0	925	10.00	1.00	10.30	10.11	10.50	--
23-81	226	27.5	60.0	925	10.08	2.10	10.42	10.30	10.70	--
-82	227	28.1	60.0	924	9.98	3.60	10.70	10.65	10.95	--
23-83	227	[illegible]	60.0	925	9.80	5.00	11.00	11.00	11.28	--
23-84	227	27.5	60.0	921	9.55	6.70	11.38	11.50	11.78	--
23-85	227	27.4	60.0	920	9.28	8.48	12.30	12.35	12.56	--
23-86	227	26.5	60.0	920	8.80	10.82	13.62	13.68	13.72	--
23-87	227	26.0	60.0	920	8.32	12.75	14.90	14.90	15.00	--
23-88	227	28.8	60.0	930	11.35	0.0	11.72	11.15	11.32	--
23-89	226	30.0	60.0	929	11.42	1.0	11.82	11.30	11.48	--
23-90	226	30.6	60.0	928	11.42	2.2	11.91	11.45	11.65	--
23-91	226	30.8	60.0	926	11.30	4.05	12.12	11.70	11.92	--
23-92	226	30.4	60.0	925	11.00	6.12	12.61	12.20	12.48	--
23-93	226	29.5	60.0	922	10.58	8.09	13.25	12.90	13.14	--
23-94	227	28.2	60.0	920	9.8	12.32	14.32	14.5	14.78	--

Appendix G

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